June 7, 2021

Dr. Christian Griebler Journal of Contaminant Hydrology Elsevier B.V., Radarweg 29 Amsterdam 1043 NX, Netherlands

Subject: Review of the Paper "Direct Aerobic NSZD of a Basalt Vadose Zone LNAPL Source in

Hawaii"; Journal of Contaminant Hydrology, Volume 235, November 2020

Dear Dr. Griebler,

We are writing to the Journal of Contaminant Hydrology (JCH or Journal) to bring to your attention both ethical and technical concerns regarding the subject paper. Our familiarity with the subject site in the JCH Paper is based on our extensive related work at the subject facility and elsewhere in Hawaii. We are subject matter experts working with the Hawaii Department of Health (HDOH) on the groundwater protection issues related to fuel storage, handling and releases at the Red Hill Bulk Fuel Storage Facility (hereafter, the "Site"). Our comments reflect our individual concerns and are not directed nor funded by the HDOH. Our professional resumes are attached for background on our areas of technical expertise. G.D. Beckett has done extensive research in multiphase mechanics, with a particular focus on how immiscible fuels behave in geologic systems, and has created technical work products for the American Petroleum Institute (API) and others on the subject. Dr. Thomas is a Geochemist and the Director for Center for the Study of Active Volcanoes at the University of Hawaii, with extensive publications on Hawaiian geology and hydrogeology. Mr. Whittier is the technical lead for Hawaii's Source Water Protection Program, with more than 25-years of Hawaii specific groundwater research and technical investigations. Collectively, we have a detailed understanding of the Site that is the subject of the JCH Paper, and more broadly Hawaiian groundwater and contaminant hydrogeology. We hope to provide additional data, insights and observations for the Journal's consideration as those relate to hypotheses and conclusions in the JCH Paper.

Based on the ethical conflicts of the Paper's authors that will be discussed, we believe the Paper should be withdrawn. Further, the severe technical limitations to the hypotheses in the Paper require, in our view, a literature correction and rebuttal. Whether either the ethical or technical limitations are sufficient to withdraw the Paper is obviously a matter for the JCH Editors to decide. If JCH decides to retain the Paper, then we respectfully request that our comments be submitted as a formal rebuttal (in a different format than this comment letter).

The authors of the JCH Paper are contractors to the US Navy (or are civilian Navy employees) tasked with evaluating the environmental impact of a 27,000-gallon fuel release in 2014 from Tank 5 and other aspects to meet regulatory compliance. The JCH Paper authors (inclusive of the Navy representative) have a direct interest in the conclusions they draw and extend more broadly to other site work. The JCH reviewers may wish to look through their public domain Conceptual Site Model Report (CSM, 2019¹) and its conclusions relative to the subject content in the JCH Paper; the executive summary of that document is attached to

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The Navy CSM Report can be found at: <a href="https://www.epa.gov/sites/production/files/2019-07/documents/red-hill-conceptual-site-model-20190630-redacted.pdf">https://www.epa.gov/sites/production/files/2019-07/documents/red-hill-conceptual-site-model-20190630-redacted.pdf</a>

this review. As reviewers of that and other Site work, we have an interest in protecting the South Oahu Basal Aquifer beneath the subject Site and to recognize the uncertainties presented by the underlying complex volcanic depositional setting. The South Oahu Basal Aquifer has been designated by the U.S. Environmental Protection Agency as a Sole Source Aquifer. The Sole Source Aquifer Designation means that this aquifer provides at least 50 percent of the drinking water for its service area (urban and suburban Honolulu, Hawaii), and that there are no reasonably available alternative water sources (U.S EPA; https://www.epa.gav/dwssa/overview-drinking-water-sole-source-aquifer-program#What\_Is\_SSA). The value of this aquifer cannot be overstated. This aquifer is one of the largest sources of potable water on the Island of Oahu and there is no viable replacement should it become impaired. The observations and objections to the JCH Paper that we share here have been previously provided to the authors of the JCH Paper, but remain unaddressed. Our main technical point in this commentary is that the Paper is inconclusive, non-conservative and conflicts with other site data. More importantly, we also believe the JCH Paper clearly violates the Journal's Declaration of Competing Interest standards.

The ethical issue is that the JCH Paper purports, among other things, to ascertain the depth of fuel penetration into the subsurface based the JCH Paper authors evaluation of downhole thermal profiles. In turn, that conclusion is used in the Site CSM report to conclude that "Based on thermal natural sourcezone depletion (NSZD) studies, LTM, and other studies indicate that LNAPL is retained in the pore spaces of the rock within approximately 30 feet (ft) beneath the tanks and has not reached groundwater. "That conclusion is directly refuted by contamination of the aquifer about 100-ft below the lower tank tunnel, including the past visual observation of free product blebs on groundwater. The position by the JCH Paper authors that fuel (LNAPL) is retained in this limited vertical horizon then provides a basis for the Navy's public position that the aquifer has not been impacted by its historic and ongoing fuel operations. In turn, that is intended to paint a picture of a low-risk condition that is counter to the available data, although a final determination regarding risk to the aquifer is pending. These Navy positions were then amplified in recent sworn testimony in a contested case hearing regarding the operating permits for the Facility, again concluding the that aquifer has not been impacted by the Navy's fuel operations.

Further evidence of ethical lapses on the part of the JCH Paper authors is their portrayal of an outside review of the Paper's thermal analysis. Dr. Bekins is a participating member of our stakeholder technical working group and is a neutral scientist (as is the USGS). In August 2019, she gave a presentation to the technical working group (inclusive of the JCH authors and Navy representatives) that was critical of the thermal evaluations and interpretations in the CSM Report<sup>1</sup> that are repeated in the JCH Paper. Her presentation was cautionary and critical of important conclusions stated in the Paper. Our own technical review overlaps with that of Dr. Bekins. She has informed us that there have been no other communications between herself and the JCH Paper authors, and that our understanding of her observations are correct. Hence, the only "helpful input" given was a technical criticism of the JCH Paper's approach with regard to thermal data and its related interpretations that have not been addressed. One of the paper authors went further in under-oath case testimony stating: "Because there's no methane here, because there's so much air flow through the system, it's highly aerobic, it has a high amount of oxygen, so the heat a little different, that's why we published the paper in the "Journal of Contaminant Hydrology," and that's why we worked with a specialist at the USGS, Dr. Barbara Bekins to evaluate this." As noted, that is false; Dr. Bekins did not work with the Paper's authors in any way. She independently reviewed their methodology, found it technically deficient, and that was her only interaction with the authors based on her noted confirmation above.

We believe the JCH Paper author's reference to Dr. Bekin's and her "helpful comments", along with the subsequent hearing testimony, to be the definition of a conflict of interest, as defined by the Journal's

Competing Interests standard. The Paper authors are also aware of the technical deficiencies we discuss herein, but have chosen to ignore those and publish anyway, again an apparent conflict with the Competing Interests standard. Other aquifer stakeholders have also shared vigorous objections to the Navy CSM, as exemplified by the attached review from the Honolulu Board of Water Supply (BWS, 2019; Attachment 5). The technical objections from the BWS also parallel our own. Their review of the thermal NSZD approach is on pages 18 – 22 of that document. However, broader aspects of the BWS review may further enlighten the JCH editorial board as to the competing interests of the JCH Paper's authors.

Given the technical objections to the thermal interpretations in the Paper prior to its publication in JCH, our view is that the primary purpose of the Paper was to support technically flawed conclusions that purport a low-risk aquifer threat condition that is unsupported or undemonstrated by a variety of other site data. In short, the publication seeks to lend credibility to a set of technical conclusions that are likely invalid and also non-conservative (as demonstrated below). While the technical deficiencies are extensive, we believe the violation of the JCH's ethical standards, and in the face of existing regulatory and other stakeholder objections, to be the primary concern. The hearing testimony demonstrates this issue quite clearly. A peer-reviewed paper in a prestigious journal such as JCH gives a veneer of credibility to the authors and their interpretations that is both undeserved and unethical.

Our technical review will cover a number of areas specific to the JCH Paper's interpretations, particularly regarding the thermal profiles. However, one over-arching issue is that there is no confirmatory data that demonstrates the interpretation of thermal profiles as to the location of LNAPL in the subsurface. Rather, as discussed, recent and existing data directly contradict that conclusion; i.e., there is no observed LNAPL where the Paper postulates it to be. Some of our key technical objections include:

- No measurements of in situ LNAPL saturations/distributions as they pertain to the Paper's interpretations. Characterization of the site is sparse;
- Non-unique and incomplete interpretation of thermal profiles purporting to locate the position of LNAPL in the formation;
- No consideration of infrastructure heating sources or sinks as the tunnel and its ventilation system;
- Heterogeneity and variation in rock thermal properties/heat diffusivity are not considered;
- The unconsolidated cap material on the Red Hill Ridge has been shown to be relatively permeable, contrary to conclusions in the Paper;
- There is uncertainty in inferred aerobic conditions;
- The Facility footprint assumed to be a surrogate for the plume footprint is undemonstrated and likely not representative;
- No known published research validating the conclusion that temperature can be used to locate LNAPL in the vadose zone and no validation data collected in this Study;
- Validation challenges in the selection of the background thermal location;
- High temperature groundwater and isothermal behavior in RHMW05 are not consistent with the conclusions of the paper.

#### LIMITED RELEASE CHARACTERIZATION

Site spatial data are sparse and the plume location, its conditions and history relative to NSZD are predominantly unknown. The interpretation of the depth of fuel impacts drawn in the JCH Paper (JCH Paper Figure 5) is unbounded by any in situ confirmatory data. Given the Site's risk sensitive context

overlying a sole-source and irreplaceable aquifer, this is a serious limitation that is not addressed in the JCH Paper or other related Site evaluations. The tank farm footprint is about 13-acres and the depth to water beneath the tanks is roughly 120-ft beneath the lower tank tunnel, for a total of about 68 million cubic feet of material. It is also important to note that the tanks extend upward for another 250-ft. from the lower tunnel (i.e., 370-ft above the water table; ~210 million cubic feet), a zone with no contaminant characterization data whatsoever. Within that area and volume, there are 2 monitoring wells that were advanced and sampled through the vadose zone from the tunnel floor to groundwater, with one additional well located about 200-ft down-ridge (see Figure 2 in the JCH Paper; wells RHMW01 - 03). These locations did not contain observable vadose zone fuel impacts at the time of installation (the boring logs are attached hereto). There are no other vertical investigation borings/wells due to safety concerns at the time of the 2014 fuel release from Tank 5. In addition, 46 slant borings were advanced previously in the late 1990s/early 2000s immediately below the tanks, with several indicating fuel impacts and a heterogeneous distribution consistent with the complex geology (Figure 1 attached here). To summarize, fuel impacts have been observed immediately below several tanks, but the vertical and lateral extent is undelineated in all directions. The Paper comes to conclusions based on the thermal profiles regarding the location of LNAPL that conflict with the available data showing no LNAPL where postulated.

Since the JCH Paper was published, RHMW01 has been reinstalled to correct well screen deficiencies. In the Navy's CSM, using the same interpretation methods, the JCH Paper authors interpreted the net thermal profile at RHMW01 to exhibit an LNAPL source located from approximately 20 - 30 feet below the lower tunnel (see CSM Section attached here). During re-installation of RHMW01, no LNAPL or related fuel impacts were detected in the vadose zone (Dr. John Kronen, email communication, March 2021). The data indicate there is no LNAPL or observable contamination at RHMW01, directly contradicting the thermal interpretations made by the JCH authors in their CSM report and validating Dr. Bekins and our own concerns about their approach. We recognize the RHMW01 is the smallest net thermal profile, but in that sense, it makes an excellent test case. Had LNAPL been found as interpreted, it would lend credence to the same for the interpretation at the other Tank Farm locations (RHMW02 and -03). The test of the hypothesis directly failed field validation. The heat source for these profiles is likely a complex network of LNAPL distributions associated with decades of varying releases at differing tanks. These tanks have been in service since the 1940s and have had reported releases of approximately 200,000 gallons of fuel and an unknown additional volume from known releases that have no loss estimates. There are too many release sources, timeframes, and fuel characteristics to support a simplistic and unique interpretation as done in the JCH Paper (Figure 5), particularly absent detailed confirmatory in situ data (LNAPL saturations, locations, chemistry, relationship to tank contents, expected impacts above the lower tunnel, etc.). The JCH Paper's premise that these profiles determine the location of in situ LNAPL is novel, but refuted by available Site data.

Another matter is the geologic complexity of hard-rock volcanic setting. Figure 2 is a cross-section from the referenced Red Hill CSM (DON, 2019) showing the interpreted lithologic conditions along the centeraxis of the Tank Farm and west toward the Navy's groundwater production shaft. As observed, there are 4 primary lithologic features: i) gravelly clinker zones, and inter-flow features; ii) pahoehoe, or ropey lava zones of thinly bedded flows; iii) massive a'a zones; and iv) voids and lava tubes. Although the key rock zones are volcanically-sourced, their hydrogeologic character varies widely, as would their thermal properties (conductivity, diffusivity, etc.). Although clearly different in implication, the same lithologic variations will affect the distribution of the fuel source and the NSZD that is the subject of the Paper. The propagation of heat is non-unique, where variations in the heat source location, intensity, the thermal diffusivity of the various rock zones, time, and other factors combine to form the resulting heat signature and profile (in this case, it is an unconstrained profile). This makes it impossible to interpret the location

of the source LNAPL absent adequate data density and measurements of where the supposed LNAPL and heat generation actually occurs in the subsurface. The JCH Paper's hypothesis on the location of the LNAPL source zone is conjectural and non-conservative (see thermal discussion below for other aspects). As noted at RHMW03, that location was devoid of hydrocarbon impacts on its installation in 2005, with no reported releases in that area since and RHMW01 was recently confirmed to contain no vadose zone LNAPL, contrary to the thermal interpretations. Hypotheses are a necessary scientific element, but validation through data collection is the standard approach, particularly in the subject case where the interpretation has direct implications to the site risk context. The Paper has no such confirmatory data. Much of their data collected during this investigation conflicts with the conclusions of the JCH Paper (e.g., the existence of an impermeable saprolite cap and the presence of LNAPL around the upper part of the RHMW03 well casing).

The JCH Paper presents degradation rates by different approaches that are then quasi-integrated across the Site footprint of 13-acres to derive degradation rates in equivalent units of gallons per acre per year. The Paper states that "This is the maximum area impacted by fuel releases from the facility assuming that lateral migration of LNAPL has been minimal." This speculative and non-conservative assumption is contrary to available site data. Although the paper notes a potential 61-acre footprint, other site data suggest a potentially much larger plume area. As reported in the Paper, two of the surface CO₂ cannisters exhibited fuel-related detections; T1 and T8, are located roughly 400 to 600 feet away from the nearest Tank Farm boundary (JCH Paper Figure 3). There have also been reported fuel contaminant detections in distal monitoring wells. The JCH Paper authors dispute those detections as being artifacts, but in our own review, we see multiple lines of evidence that they are valid. Of note, while those detections are generally small and intermittent, they are comparable with the measured CO2 flux cannister distances away from the Site. As another data confirmation of the potential plume size, in 2017 the Navy collected soil vapor samples from the Site vapor probes and four monitoring wells included in the JCH Paper (RHMW01 – 04; lab results are attached). Fuel hydrocarbon vapors were detected at RHMW04, a distal well approximately 850-ft away from the facility (see JCH Paper Figure 2). This location has also had infrequent, low-level fuel-related detections reported in groundwater. This particular location is in the opposite direction of the generalized contaminant and groundwater flow pathways assumed in the CSM. The totality of available site data suggest that fuel impacts are widespread, complex, and that interpretations in the JCH Paper directly and non-conservatively conflicts with these data. These observations are also consistent with those observed at other Hawaiian fuel releases in the volcanic rock setting.

We estimate, based on these geographic data points, that the plume footprint generating the CO<sub>2</sub> could be approximately an order of magnitude larger than the assumed 13-acre Tank Farm footprint. While a true integration cannot be done with the sparse site data, one can simply observe that the plume(s) generating CO<sub>2</sub> is much larger than the Site footprint. Therefore, the JCH Paper underestimates the potential plume area and greatly overestimates the degradation rates on a gallons/acre/year basis. This is also corroborated by the thermal profile at RHMW03, which is the most robust measured. There have been no reported releases in over 20 years in that vicinity. At the kind of robust degradation rates reported in the JCH Paper using their 13-acre footprint, this suggests that the release there must have either been very large, or that the degradation rates are much smaller than estimated (or both). Whatever the case, biodegradation has clearly not remediated impacts at that location after more than 20 years of presumed ongoing mass depletion (or longer, as the release character is not known, and lead - Pb detections may suggest an even older series of releases). NSZD can be considered as one process in appropriate groundwater protection strategies, as should the related time to cleanup completion. The ongoing and apparently robust degradation in the area of RHMW03 over at least 20 years suggests that NSZD may not occur at rates sufficient for aquifer protection goals (that determination has yet to be

made). In summary, the JCH Paper makes an unsupported plume area assumption that creates the perception of very high degradation rates on an area-wide basis that are not consistent with available site information and lead to non-conservative interpretations regarding the risk to the aquifer. Again, we believe this was the Paper author's intent in its publication; to give credibility to unsupported and non-conservative conclusions that have met with objections by us and other aquifer stakeholders. To our knowledge, no party to this case agrees with the conclusions of the JCH Paper (excepting its authors).

Finally, another undelineated aspect of the JCH Paper is the assumption of fully aerobic conditions leading to the conclusion that the thermal profile is a direct indication of the LNAPL location (particularly in the vertical dimension). The paper does note that this may not be universally true throughout the formation and we concur. The issue is again one of limited characterization coupled with complications caused by lithologic heterogeneity and historic release transport within this setting. To appropriately make this assessment, one would need to spatially delineate the various zones of fuel impacts and couple that with zone-discrete vadose zone vapor data to couple into a cogent and confirmed set of related conditions. Because the Tank tunnel acts as a vapor capture system (due to ventilation systems), oxygenated air will mix with that from impacted intervals to result in weighted averages. Because of the large volume of subsurface materials below the Red Hill ridge, it is not possible to determine if aerobic conditions are actually present at the in-situ locations where LNAPL is degrading. The lithologic conditions vary at each Tank, so every release area would be expected to have a different sequence of behaviors, in turn overprinted by the multiple releases that have likely occurred over the long history of fuel operations. This evaluation would also need to be coupled with the noted active vapor flow into the Site tunnel due to ventilation systems. Since the lithologic distribution is heterogeneous, so would be the expected vapor flow, LNAPL distribution and degradation conditions. In a hard-rock setting like this, we expect zones of high flow, impeded flow, dead-end macro-pores, etc. Therefore, while we agree that the available data seem to indicate near-aerobic conditions at the limited sampling locations, those cannot be placed in context with measured LNAPL impacts. The hypothesis of aerobic conditions is based on sparse data and continuous advective vapor flow, with no understanding of the fuel distribution or degradation mechanics of the subsurface system. When breaking new ground in scientific endeavors, validation through groundtruth and data is the standard approach. The JCH Paper fails to do that and the available data conflicts with many of its assumptions and hypotheses.

# HEAT SOURCES & NET HEAT

The JCH Paper selects RHMW05 as the background thermal profile from which the excess heat is determined at other locations by subtraction. There are several issues with this selection. First, RHMW05 exhibited no impacts in the vadose zone when installed and minor impacts to groundwater, but it has the highest groundwater temperature of all locations tested except RHMW03. All in-tunnel wells exhibit substantially elevated groundwater temperatures relative to distal well locations. However, there is relatively cooler water between RHMW03 and RHMW05 (at RHMW01 and -02), indicating that this is not a simple case of heat transport in groundwater (advective and diffusive). RHMW05 exhibits an unusual heat profile that it is nearly isothermal above the water table. These observations suggest it is not a suitable background well where, absent outside heat sources, the profile is expected to be sloping from the water table to the tank tunnel. RHMW05 does not meet those criteria. Dr. Bekins in her critique noted the importance of validating the selection of background conditions, which was not done in the Paper.

Beyond the anomalous behavior at RHMW05 is the broader question of whether any of the in-tunnel locations are representative of background conditions that can be applied to the net heat profiles. As

noted in the JCH Paper, RHMW01 may be a more suitable background location, but it also may not. These monitoring wells are all installed within the tunnel system of the Red Hill Tank Farm. They are not under natural conditions, and there are so few wells characterizing both heat and LNAPL impacts, that it is unclear if background can be defined (absent new and extensive investigatory data). An analysis that might help that determination would be to consider and estimate the thermal input (or depletion) from the facility itself. The Site has an enormous fuel throughput and storage, as well as the facility infrastructure, that likely have thermal effects. Although the Navy reportedly measures fuel temperatures, an analysis of the thermal impact of the facility operations was not considered in the JCH Paper. As noted by Askarani et al. (2018) in their work, the thermal effects from infrastructure can be significant. Further, the JCH Paper is likely in error regarding the background temperature in the lower tunnel (i.e., the Honolulu Airport is not an appropriate baseline). Our local HDOH weather station at the same elevation as the Site registers about 23 °C in the relevant timeframe (an expected decrease with increasing elevation). This implies the lower tunnel may be a heat sink that creates the "bulge" in the tunnel thermal profiles that are a key basis for the JCH Paper's conclusion about the LNAPL location in the subsurface. A thorough analysis of this aspect, coupled with characterization of the actual lateral and vertical locations of fuel sources, would be necessary to assess whether or not there are any suitable background wells and develop constraints on the interpretation of the thermal profiles as used in the JCH Paper. While we believe the thermal profiles indicate "something" related to biodegradation of fuels, what that is cannot be determined at present.

As noted above, the wells at which a net excess heat profiles were calculated were "clean" in the vadose zone on installation, as was recent new testing at RHMW01. In the case of RHMW03, there have been no reported or suspected leaks in that area since its installation. At well RHMW02, there was a release at Tank 5, but also elevated impacts beneath the closer Tank 6 in the slant borings of 29,500 mg/kg total hydrocarbon, one of the largest detections at the facility within the available data set. Further, the vapor probes discussed in the JCH Paper indicated that, at those specific sampling points, the fuel vapor transport was observed to the northwest of Tank 5 in the opposite direction of RHMW02 (further observations of its behavior do not exist). While the JCH Paper does not draw clear conclusions regarding the thermal profile at RHMW02, their CSM does and concludes that the 2014 release did not travel any further than ~30-ft below that tank (like their interpretation at RHMW03). It is a conclusion in apparent conflict with available data and is why the thermal interpretation aspects of the Paper are important, both from a broad scientific inquiry and the site-specific perspectives. Again, the most important observation is that the Paper's unique interpretation of the thermal profiles is not supported by available site data.

# RELATIVELY IMPERMEABLE RIDGETOP SAPROLITE

The JCH Paper suggests that the ridgetop setting of the Site has a relatively impermeable saprolite cap. In turn, that conclusion is used to premise other conceptualizations that are undemonstrated and also relate to interpretations in their CSM (2019, see above). This interpretation is counter to site data and Hawaiian hydrogeologic conditions.

Double-ring infiltrometer testing was performed by the Navy contractors on the Site's ridge-top saprolite materials at three locations (the results table is below). Assuming a gravitational gradient, one can estimate that the field-saturated vertical hydraulic conductivity of the saprolite varied between about 8 to 17 ft/day. For a Hawaii-specific context, those values are in the same range, though slightly larger, than the vertical conductivity of the regional productive basalt aquifer zones (e.g., Souza, W.R., and Voss, C.I., 1987; Oki, 1995). In that aquifer evaluation work, a value of about 7.5 ft/day is used in the regional

context. Simply put, the ridgetop at Red Hill has approximately the same vertical permeability as the regional aquifer system it overlies, recognizing that there is spatial variability that a regional groundwater model will not consider. It is not representative to conclude, as the JCH Paper does, that it is relatively impermeable, as the ease of infiltration from the highlands demonstrates that rainfall percolates readily into this system without significant pooling or runoff for most events. In other words, there is no practical evidence that the thin saprolite caps are relatively impermeable. However, it is representative to note that the contrast between vertical and lateral hydraulic conductivity (or vadose zone permeability) in Hawaiian basalt sequences is relatively large, as one might expect of these types of stratigraphic sequences.

TABLE 1 – SITE INFILTROMETER TESTING RESULTS

	Final Infiltration Rate			Soil Classification
Test No.	(cm/hour)	(inch/hour)	(ft/day)	(USCS)
IF-1	20.6	8.11	16.22	Silty Clay (CH)
IF-2	10.7	4.21	8.42	Silty Clay (CH)
IF-3	22	8.66	17.32	Clayey silt (MH)

Table Transcribed from Table 5.3 in the Redacted Red Hill CSM (2019; citation above). The column "ft/day" is calculated based on the conversion from "inches/hour".

# SUMMARY

In summary and in our view, the JCH Paper authors have violated the competing interests policy of JCH. To our knowledge, every stakeholder to this project and aquifer protection has objected to various aspect of the Paper in the public record. The Paper authors are fully aware of these conflicts and technical objections. They declined to address those and published the Paper anyway. The JCH could not have been aware of these issues and the Paper authors should have brought these issues to the attention of your Editors and technical reviewers. They purposefully chose not to do so.

Beyond the ethical matter, the JCH Paper has severe technical deficiencies relative to the available data and the non-conservative manner in which key assumptions are made, creating a perception of very large biodegradation rates that the limited data suggest is likely less robust. The USGS reviewer (Dr. Bekins) identified significant technical deficiencies with the Paper's thermal NSZD approaches, as have we and other stakeholders. As noted, those remain unaddressed by the Paper's authors.

Depending on the conclusions of the Journal regarding what actions might be taken regarding the subject Paper, we can provide a formal rebuttal for publication, or leave this as an internal matter for the Journal to address. When the Journal determines its recommended actions, we request that there be a public record of the decision. We also recommend that the Journal request a peer-review from Dr. Bekins, if she is able. The JCH Paper authors want to support technically indefensible conclusions that have a non-conservative impact on the interpretation of the potential risks to drinking water beneath the subject Site. We believe that is both technically and ethically questionable, given our critique above and the limitations it imposes on the conclusions of the JCH Paper.

At your convenience, please advise on how the Journal would like to proceed in this matter and we will oblige in providing a formal rebuttal, additional information, or whatever else the Journal may request. We appreciate your assistance in resolving this matter.

Sincerely,

Mr. G.D. Beckett, C.Hg.

Hydrogeologist & Multiphase Expert

AQUI-VER, Inc., Park City, Utah

Dr. Donald Thomas

Geochemist and Director Center for

Devald Hloman

the Study of Active Volcanoes

University of Hawaii

Mr. Robert Whittier

an u

Technical Lead – Hawaii's State

Water Protection Program & Affiliate Faculty, Water Resources

Research Center, University of Hawaii

# REVIEWER CIRICULUM VITAES

# G.D. BECKETT, Hydrogeologist & President

Mr. Beckett is the Proposition of the Proposition o

Under Mr. Be ckett's guidance and publishing, AQUI-VER, INC. (AVI) has developed new scientific techniques and analyses to evaluate multiphase contaminant transport, remediation, and environmental risk. These new and rigorous science applications have led to an outstanding cleanup and closure record. Science has been shown to describe real processes that control site environmental risk and the design of efficient and effective cleanup systems (as needed). These technical credentials have allowed Mr. Beckett toprovide training to regional regulatory agencies, including the EPA and others, on behalf of industry groups including the American Petroleum Institute. Mr. Beckett is a leader in the field of non-aqueous phase liquid (NAPL) contamination and cleanup including petroleum products, solvents, oils, and other compounds.

# **EDUCATION & CERTIFICATIONS**

- \* California Registered Geologist
- \* California Registered Hydrogeologist
- \* M.S., Geology, Hydrogeology Emphasis, San Diego State University (4.0/4.0 GPA)
- \* B.S., Geology, Hydrogeology Emphasis, San Diego State University.
- \* 40 hour OSHA 29 CFR 1910.120; 8 hour OSHA Annual Refresher
- \* Pertinent Course Work
  - Hydrogeology
  - Sedim entology
  - Well Hydraulics and Testing Methods
  - Exploration Techniques in Ground Water (audit)
  - Solute Transport

#### EDUCATION (continued)

- Numerical Modeling of Fluid Flow in Geologic Media
- Immiscible-Phase Fluid Hydraulics in Porous Media
- Behavior of Subsurface Organic Contaminants (audit)
- Vapor Phase Dynamics and Transport of Organic Compounds
- Conference; Immiscible-Phase Organic Contaminants in Porous Media. Conference focused on the principles and modeling of immiscible-phase organic contaminants in the subsurface, and remediation strategies.
- Organic Chemistry
- Geochem istry
- Ground Water Geochemistry
- Environm ental Chemistry
- Risk Assessment
- Conservation of Environmental Quality
- Other related science and math course work

#### ACADEMIC AND PROFESSIONAL HONORS

- \* Awarded Outstanding Senior Thesis by Faculty and Peers
- \* Awarded a Scholastic Scholarship for Master of Science work by the AcademRewards for College Scientists (ARCS) Foundation
- \* Guest Lecturer, 1993 Graduate Course in VaporPhase Dynamics and Transport of Organic Compounds in the Vadose Zone, Department of Geological Sciences, San Diego State University. Instructor: Donn L. Marrin.
- \* Guest Lecturer, 1994, 1995, Graduate Course in Well Hydraulics, Department of Geological Sciences, San Diego State University. Instructor: David Huntley.
- \* Certificate of Honorable Mention, 1997. In Recognition of Presentation Excellence and Scientific Quality of the Paper. Division of Environm ental Geosciences, Am erican Association of Petroleum Geologists (AAPG).
- \* Instructor, 1997, 1998, 1999, 2000, 2001, 2003, 2004, 2005. Conference work shops on various aspects of multiphase mechanics, LNAPL recovery, model parameterization, and risk. Hosted by the Am erican Petroleum Institute and preceding the Petroleum Hydrocarbons & Organic Chem icals in Ground Water Conferences, sponsored by the National Ground Water Association & American Petroleum Institute.
- \* Graduate Course Instructor, 1998, Multiphas&Flow, Geology 651, Department of Geological Sciences, San Diego State University. Course in multiphase flow, remediation and risk.

#### ACADEMIC AND PROFESSIONAL HONORS (continued)

- \* Short-course Instructor, March 2000, Multiphase Screening Methods to Determ ine Fuel Immobility in Soil, AEHS West Coast Conference, San Diego, California.
- \* Short-course Instructor, March 2002, Assessm ent of LNAPL Sources; Distribution, Mobility, Risk and Risk Reduction. AEHS West Coast Conference, San Diego, California.
- \* Chairman, ASTM E50.04 Task Group on LNAPL 2002 2006. This E50.04 task group is responsible for preparing a Guide entitled: Working DRAFT 2: Standard Guide for Development of Conceptual Site Models and Remediation Strategies for Light Non-aqueous Phase Liquids Released to the Subsurface. The first document ballot was in July 2005.
- \* Invited Speaker, 2005 National Underground Storage Tank Fund Administrators Meeting, Salt Lake City, Utah, sponsored by EPA OUST and ASTSWMO.
- \* Instructor, 2006, American Petroleum Institute University Course on LNAPL principles, and instruction on use of the API Interactive LNAPL Guide.
- \* Instructor, 2008, Course on Applied LNAPL pinciples and tools for the Hawaii Department of Health, U.S. EPA, U.S. Navy, U.S. Air Force and related participants.
- \* Former member of the AEHS West Coast Conference Science Advisory Board.
- \* Journal reviewer; Groundwater Monitoring and Remediation
- \* Past Journal reviewer; Journal of Contaminant Hydrology

#### **PUBLICATIONS**

- \* Beckett, G.D., Huntley, D., 1994, Characterization of Flow Param eters Controlling Soil Vapor Extraction: Ground Water, Vol. 32, No. 2, pp. 239-247.
- \* Beckett, G.D., Huntley, D., 1994, The Effect of Soil Char acteristics on Free-Phase Hydrocarbon Recovery Rates: Proceedings of the Petroleum Hydrocarbon and Organic Chemicals in Ground Water; November 2-5, 1994, Houston, Texas, NGWA, API.
- \* Beckett, G.D., Huntley, D., Panday, S., 1995. Air Sparging: A Case Study in Characterization, Field Testing, and Modeling Design. Proceedings of the Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection and Restoration, Houston, Nov. 1995.
- \* Beckett, G.D., Benson, D.A, 1996. Diffusion Limited Soil Vapor Extraction: Geologic and Bed Thickness Controls. AAPG Annual Convention, San Diego, California, May 1996.

#### **PUBLICATIONS** (continued)

- \* Beckett, G.D., Huntley, D., W iedlin, M.P., 1996. Hydr ocarbon Fate and Transport Predictions: When Are One-dim ensional Solute Transport Calculations Valid? AAPG Annual Convention, San Diego, California, May 1996.
- \* Beckett, G.D., Huntley, D., 1997. HydrocarbonFate and Transport Predictions: When Are One-dimensional Solute Transport Calculations Valid? (Upda ted). AEHS W est Coast Annual Convention, Oxnard, California, March 1997.
- \* Huntley, D., Beckett, G.D., 1997. The Life and Times of LNAPL Pools. An investigation into the lifespan and time-dependent magnitude of dissolved-phase inpacts from free-phase hydrocarbon pools. AEHS Annual Convention, Oxnard, California, March 1997.
- \* Beckett, G.D., Lundegard, P.D., 1997. Practically Impractical The Limits of LNAPL Recovery and Relationship to Risk. Conference Proceedings of the 1997 Petroleum Hydrocarbons & Organic Chemicals in Ground Water. Houston Texas, sponsored by the National Ground Water Association & American Petroleum Institute.
- \* Huntley, D., Beckett, G.D., 1997. Persisten ce of LNAPL Sources and Re lation to Risk. Conference Proceedings of the 1997 Petrol eum Hydrocarbons & Organic Chem icals in Ground Water. Houston Texas, sponsored by the NGWA and API.
- \* Beckett, G.D., Huntley, D., 1998. Sil Properties and Design Factors Influencing Free-phase Hydrocarbon Cleanup. January 1998, Environmental Science and Technology.
- \* Huntley, D., Beckett, G.D., 1999. Relati onship Between Risk Reduction and LNAPL Recovery. Conference Proceedings of the 1999 Petroleum Hydrocarbons & Organic Chemicals in Ground W ater, Houston, Texas, sponsored by the National Ground W ater Association & American Petroleum Institute.
- \* Peargin, T.R., Wickland, D.C., Beckett, G.D., 1999. Evaluation of Short TermMultiphase Extraction Effectiveness for Removal of Non-Aqueous Phase Liquids from Groundwater Monitoring Wells. Conference Proceedings of the 1999 PetroleumHydrocarbons & Organic Chemicals in Ground W ater, Houston, Texas, sponsored by the National Ground W ater Association & American Petroleum Institute.
- \* Lundegard, P.D., Beckett, G.D., 2000. Practical yof LNAPL Recovery Implications for Site Management. Battelle 2nd International Conference on Remediation of Chlorinated and Recalcitrant Compounds; May 2000.
- \* Beckett, G.D., 2000. Soil Vapor Extr action under Capped and Uncapped Surface Conditions. Geotechnical Fabrics Review; vol. 18, #4.

# **PUBLICATIONS** (continued)

- \* Beckett, G.D., 2000. Remediation is Enhanced Oil Recovery: Know Your Source. AAPG & SPE Convention, Long Beach, California, June 2000.
- \* Huntley, D., Beckett, G.D., 2002. Persistence of LNAPL Sources: Relationship Betwe en Risk Reduction and LNAPL Recovery. Journal of Contaminant Hydrology, #59, pp 3 26.
- \* Huntley, D., Beckett, G.D., 2002. Evaluating Hydrocarbon Removal from Source Zones and Its Effect on Dissolved-Phase Plume Longevity and Magnitude. API Publication 4715.
- \* Beckett, G.D., Joy, S.P., 2003. Light Non-Aqueous Phase Liquid (LNAPL) Param eters Database, Version 2.0, Users Guide. API Publication 4731, December 2003.
- \* Beckett, G.D., 2003. Light Non-Aqueous Phase Li quid (LNAPL) Param eters Database, Professional Poster, 2003 PetroleumHydrocarbons & Organic Chemicals in Ground Water, Costa Mesa, California, sponsored by the National Ground Water Association & American Petroleum Institute.
- \* Parcher, M., Beckett, G.D., & Thota, P., 2004. The API Interactive LNAPL Guide. This is a digital publication of instructional m aterial and quantitative tools related to LNAPL interactions and rem ediation in the subsurface. Introduced at the 2004 Petroleum Hydrocarbons & Organic Chemicals in Ground Water, Baltimore, Maryland, sponsored by the National Ground Water Association & American Petroleum Institute.
- \* Lyverse, M.A., Beckett, G.D., 2004. Field Study of LNAPL and Dissolved-Phase Plume Genesis. Presented at the 2004 Petroleum Hydrocarbons & Organic Chemicals in Ground Water, Baltim ore, Maryland, sponsored by the National Ground Water Association & American Petroleum Institute.
- \* Beckett, G.D., Lyverse, M.A., 2004. NAPL Immobilization; When & Why It Stops, & Other High-Level Observations. Pr esented at the 2004 Petroleum Hydrocarbons & Organic Chemicals in Ground Water, Baltimore, Maryland, sponsored by the National Ground Water Association & American Petroleum Institute.
- \* Beckett, G.D., 2004. Got NAPL? Editorial. Groundwater Monitoring and Rem ediation. 2004, Volume 24; Number 4, Pages 4-6.
- \* Beckett, G.D., 2004. The LNAPL Param eters Database; Content, Param eter Ranges & Implications. Presented at the 2004 Petrol eum Hydrocarbons & Organic Chem icals in Ground Water, Baltimore, Maryland, sponsored by the National Ground Water Association & American Petroleum Institute.

#### **PUBLICATIONS** (continued)

- \* Beckett, G.D., Parcher, M.A., 2005, editors & key authors of the API Interactive LNAPL Guide (V. 2.04), a digital compendium of LNAPL resources, calculation tools, and educational materials. Copyright American Petroleum Institute, 2005.
- \* Beckett, G.D., Stanley, C.C., Walsh, D.F. 2005. Safe Groundwater Use in the Presence of a Proxim ate MTBE Plum e: Use of Flux and Transport Based Estim ates to Ens ure Groundwater Production Capacity. NGWA Groundwater Summit, 2005, San Antonio, TX
- \* Charbeneau, R. Beckett, G.D., 2006, User's Guide for the LNAPL Distribution and Recovery Model (LDRM), American Petroleum Institute, 2007.
- \* Beckett, G.D., 2007, The Vapor Pathway; It's Gas. A Panel Presentation & Discussion on Vapor Pathway Issues Pertaining to Property Redevelopm ent. RTM Conference on Contaminated Property Transactions, Promoting Sustainable Deals and Rede velopments. San Francisco, November 2007.
- \* Beckett, G.D., 2008. Improving the California UST Cleanup Process; Where Are We Now & Where Do We Go from Here to Better Ta rgeting the "Source" Zone. AEHS Annual Convention, San Diego, California, March 2008.
- \* Beckett, G.D., 2008. The ASTM LNAPL Guide: What it Is, Why It's Needed, What it Can Do. AEHS Annual Convention, San Diego, California, March 2008.
- \* Beckett, G.D., 2008. Session Chair & Speaker: Remediation Retrospective: What Can We Learn from Failed Remediation Efforts. AEHS Annual Convention, San Diego, California, March 2008.
- \* Beckett, G.D., & Bell, D., 2009. Contrasts in LNAPL Risk Factors for Different Petroleum Products. Remediation Technologies Symposium 2010, Banff, Alberta Canada.
- \* Beckett, G.D., & Huntley, D., 2015. LNAP L Transm issivity: A Twisted Param eter. Groundwater Monitoring and Remediation, Volume 35, Issue 3, Summer 2015.
- \* Beckett, G.D., & Huntley, D., 2015.LNAPL Transmissivity: A Twisted Parameter. Poster Presentation, National Underground Tank Conference, September 2015.
- \* Beckett, G.D., 2017. How Suing Manufacturers Is Different from Lawsuits Against Local Responsible Parties; Differences in Technical Approach, Analyses & Testimony. American Groundwater Trust, California Groundwater Law Conference. San Francisco, CA.

# ANALYTIC EVALUATIONS AND MODELING EXPERIENCE

- \* Extensive familiarity with analytic modeling and analysis techniques, including development of related software. Testing and evaluation conditions include confined, unconfined, leaky, fractured, anisotropic, and other flow conditions by any of several analytic techniques.
- \* Vadose Z one T esting Familiar with G uelph and open-hole permeameter testing and analysis. Working knowledge of tensiom eter, lysimeters, gamma logs, and other vadose zone monitoring equipment and down-hole geophysics.
- \* SVE Testing Developed transient vapor extraction test m ethodologies as published by Journal of Ground Water (1994). Extensive evaluations of vapor recovery and c hemical partitioning data as pe rtain to cleanup design, cleanup lim its, and vapor-phase health/environmental risk.
- \* Sparge Testing Developed physical/chem ical testing m ethodologies to relate field effectiveness diagnostics to cleanup goals and system design. This study was part of a Petroleum Environmental Research Forum (PERF) investigation.
- \* Dual-phase Recovery Developed diagnostic dta collection protocols for a prime contractor working on several military installations. Determined that many standard methods of dual-phase cleanup often fail to treat zones of interest below the water table.
- \* Extensive familiarity with numerical models pertaining to ground water flow, unsaturated zone flow, multiphase flow, contaminant transport, and remediation, as well as programing capability in Basic, VisualBasic and C.
- \* With coauthor David Huntley, developed a multiphase analytic model and software to evaluate the relationship between fuel sources in the water table region, cleanup strategies, contaminant transport, and risk. Funded by the American Petroleum Institute.

#### PROFESSIONAL WORK HISTORY

- \* March 1992 Pr esent: President and Hydrogeologist at **AQUI-VER, INC.** (AVI), Hydrogeology, W ater Resources & Data Services. AVI specializes in quantitative hydrogeologic services including contaminant fate and transport evaluations, remediation design and feasibility assessment, and human health risk assessment. Mr. Beckett directs research and projects in those areas.
- \* January 1992 2004: Research Associate, Sa n Diego State University. This unsalaried position focused research on better understanding of contaminant migration, cleanup and risk. Research includes extensive use of computer modeling and field data examination.

# PROFESSIONAL WORK HISTORY (continued)

- \* December 1989 March 1992: Project Manager (prometed to senior at 2 year review), Alton Geoscience. Responsible for the direction of environmental studies, site closure strategies, reporting, and regulatory coordination. Duties included point person to Exaco Refining and Marketing Inc., technical leader in the Surface Testing and Remediation Planning Group, corporate hydrogeologic peer reviewer, hydrogeologic trainer, and other tasks.
- \* January 1989 December 1989: Environmental Analyst, ERCE Environmental and Energy Services Company. Responsible for field data collection, report generation, and general support tasks at a variety of sites including m ilitary bases, service stations, and industrial sites. Duties were later expanded to include field project management.
- \* March 1988 December 1988: Hydrogeologic FieldTechnician, working part-time with Dr. David Huntley, Professor of Geological Sciences, San Diego State University.

#### REPRESENTATIVE PROJECTS

- \* Technical Neutral Advisor to Federal Magistrate Judge: At the request of parties to a major case involving millions of gallons of petroleum-related contamination, Beckett has served as a neutral advisor to the Federal Judge overseing settlement proceedings in the case. The work involves extensive review of technical dta, materials, and presentations, and advising the Judge in nontechnical terms as to the meaning of this information.
- \* American Petroleum Institute: Developed a toolkit entitled "Evaluating the Necessity of Hydrocarbon Removal from Source Zones: Took for Assessing Risk Reduction." This work incorporates multiphase flow and remediation dynamics with dissolution of chemicals from the LNAPL source to allow users to estimate the risk magnitude and longevity from different release and cleanup conditions. It also all ows the user to consider the risk/benefit of remediation efforts and cost. API Publication 4715, September 2002.
- \* American Petroleum Institute: LNAPL Parameter Database. AVI's extensive experience in multiphase applications has demonstrated that many of the controlling parameters have been non-representative in past literature. This is partly due to the focus of that literature being either agricultural or reservoir related. In situ environmental conditions differ from those, suggesting a benefit to compiling applicable parameters focused on environmental applications. Using our extensive in-house LNAPL parameter database coupled with industry contributions, a query-driven database was developed that allows the user to select from a more representative range of values for various key factors. API Publication 4731, December 2003.
- \* New Pacific Properties Designed the feld and proof of concept program for a multimillion dollar rem ediation of a form er refinery that required cleanup of petroleum chemicals, including MTBE. The remediation program was implemented by IT Corporation. Using an innovative approach that optimized multiphase synergies, the cleanup reduced impacts to

#### REPRESENTATIVE PROJECTS (continued)

below human health-based standards in less than 6-months, and a no further action letter was received from the California Regional W ater Quality Control Board, allowing residential development to proceed. Through AVI's approach, it became clear the original renediation design by others using standard industry approaches was insufficient to meet the cleanup goals because it did not consider the multiphase/multicomponent aspects of the cleanup.

- \* Confidential Client Designed a state-of-the-science controlled field study of air-sparging to lead to feasibility assessment and design at a hydrocarbon-affected site. Tasks included multiphase numerical modeling, pilot study workplan and direction, refinement of numerical results, feasibility assessment, and system design. The project was part of a Petroleum Environmental Research Forum (PERF) studyon air sparging. The cleanup design predicted operations to be complete in less than 1 year (for benzene), actual system run-time was 6 months. This study showed common air sparging bubbling models to be physically incorrect.
- \* Confidential Client Performed a Human Health Risk Assessment for a site underlain by a plume containing petroleum compounds significantly above regulatory action levels and overlying a utilized drinking water aquif er. Rigorous but inexpensive information was collected to ground-truth the chemical fate and transport component of the risk assessment. Results of the risk assessment indicated less than de minimis risk and the site received a site closure letter from the lead agency (no fourther action under current site operations and conditions).
- \* Confidential Client In a two-party litigati on, performed technical work to support the defendant in showing their contribution to a major groundwater contamination plume was *de minimis*. The binding arbitration judgment found fully in favor of the defendants, with the judge describing the plaintiff's experts antheir work as non-credible. Judge's quote: "In the Arbitrator's opinion, Plaintiff's experts we re not testifying as scientists; i nstead they were testifying as advocates. Their testimony was in every way inferior to testimony of the Defendant's experts. In short, defendant's experts were believable, plaintiff's were not."
- \* Confidential Client At a terminal facility in South Carolina, one company had been named the sole responsible party for a multiparty terminal site by the regulator y agency. In coordination with the agency and that company, AVI directed collection of a robust data set including multiphase and forensic information to support development of a rigorous conceptual site model. That conceptual site model indicated that in fact, the named party was not responsible for the majority of impacts. This work resulted in the agency reversing its original decision and naming several other parties as responsible for the cleanup. This resulted in a savings of more than \$2 million dollars for the minimally responsible party.

#### **CURRICULUM VITAE**

#### Donald M. Thomas

#### **Education**

B.S. Chemistry and Physics, Dickinson College (Graduated Cum Laude), 1970
 M.S. Electrochemistry, Oregon Graduate Center, 1972. Thesis: The Pressure Dependence of Hydrogen Adsorption on a Platinum Electrode
 Ph.D. Chemistry, University of Hawaii, 1977. Thesis: An Isotopic Profile of Gases from the Summit and Flank of Kilauea Volcano

# **Professional Experience**

1998 to Present:	Geochemist, University of Hawaii, Hawaii Institute of Geophysics.
1995 to Present:	Director, Center for the Study of Active Volcanoes, University of Hawaii,
	Hilo Campus.
1987 to 1998:	Associate Geochemist, University of Hawaii, Hawaii Institute of
	Geophysics.
1980 to 1987	Assistant Geochemist, University of Hawaii, Hawaii Institute of
	Geophysics.
1977 to 1980	Assistant Researcher, Research Corporation of the University of Hawaii.
1974 to 1977	Research Assistant, Department of Chemistry, University of Hawaii.
1973 to 1974	Teaching Assistant, Department of Chemistry, University of Hawaii.
1970 to 1971	Technician in Image Optics and Photography, National Institute of
	Standards and Testing.
1969	Laboratory Assistant in Image Optics, and Photography, National Institute
	of Standards and Testing.
1966 to 1970	Laboratory and Technician Assistant, Department of Physics, Dickinson
	College.

# **Society Membership**

American Chemical Society - Geochemistry Division American Geophysical Union Geothermal Resources Council International Geothermal Association International Association of Geochemistry and Cosmochemistry

#### **Instructional Responsibilities**

The Geochemistry of Volcanic Gases: module taught for International/Professional Training Program with the Center for the Study of Active Volcanoes.

#### **Professional Service**

Subject Matter Expert, Geochemistry, Hawaii Department of Health, Review of investigation of fate and transport of contaminants from U.S. Navy Red Hill Fuel Storage Facility

Chair, Research Advisory Committee of the NELHA (Natural Energy Laboratory of Hawaii Authority) Board of Directors, 2009 - 2014

Member, Research Advisory Committee of the NELHA (Natural Energy Laboratory of Hawaii Authority) Board of Directors, 1991 - Present

Member, NELHA Board of Directors, 1991 – 2014

Member, Hawaii State Earthquake and Tsunami Advisory Committee, 1999 - Present

Chair, Hawaii State Earthquake Advisory Committee 2008 – 2012

Manager of Drilling, Hawaii Scientific Drilling Project 1996 - 2007

Member, Hawaii Hazards Forum, 2000 - 2014

Member, Mauna Kea Environmental Advisory Committee, 2005 – Present

Board of Directors of DOSECC 1997-2004

Chair, Geothermal Technical Advisory Committee (to the Hawaii Department of Land and Natural Resources), 1992 – 1996

#### **International Professional Service**

The CSAV International Training course in Volcano Hazards Monitoring is offered as a service to scientists and technicians from developing countries and the international volcanological community. To date we have provided intensive volcano hazards training to more than 250 trainees, from 28 countries. The program is offered in collaboration with the Hawaiian Volcano Observatory and the USGS Volcano Disaster Assistance Program.

#### **Public Service** (through CSAV)

Teacher Training Workshop – Incorporating Tsunami, Eruption, Earthquake and Hurricane awareness into primary, intermediate, and secondary educational curricula

Earthquake Preparedness Community Outreach: Retrofitting for earthquake survival

Natural Hazards Symposia – Tsunami, Earthquake, Eruption Hazards, Hurricanes, Flash Floods He'e Nalu: Tsunami Awareness for young adults (a video presentation)

Earthquake and Eruption Hazards on the Island of Hawaii (a video presentation for classroom use)

Lava Flow Hazards on the Island of Hawaii (a computer animation of lava flow trajectories from Hawaii's active volcanoes)

All Hazards Awareness for Students (an ongoing program of classroom visits to Hawaii Island schools)

Earthquake Retrofits for Post and Pier Structures (a web based expert system to assist homeowners in planning and executing an earthquake resistant retrofits to post and pier dwellings: http://www.hilo.hawaii.edu/~nathazexpert/expertsystem/flash\_path\_fix.php)

#### **Research Interests**

Geothermal exploration geochemistry: determination of chemical and isotopic composition of groundwaters and soil gases as tracers of leakage from geothermal reservoirs. The application of elemental and isotopic ratios of dissolved rare gases in the characterization of geothermal reservoirs.

Geothermal production geochemistry: interpretation of the chemical and isotopic composition of geothermal production fluids in terms of reservoir production characteristics, production aquifers/fluid sources, scaling/ corrosion characteristics and potential environmental impacts and the analysis of the fluids from the Kilauea East Rift Zone as an analog of seafloor hydrothermal systems.

Deep hydrology of ocean island volcanoes: evaluation of chemical compositions of deep fluids present in ocean islands as indicators of their sources and the reactions they have undergone during their passage through the island.

Application of isotopic and ion chemistry to groundwater storage and transport in complex volcanic terrain.

# **Current and Recent Projects**

An assessment of Hawaii's Geothermal Resource Potential, the Play Fairway Project (with Nicole Lautze, Neil Fraser, Steve Martel).

Determination of fate and transport of fuels released from the US Navy Red Hill Fuel Storage Facility and assessment of risk to groundwater and drinking water sources (Hawaii Department of Health).

Groundwater Hydrology in the Humu'ula Saddle Region

Spectral SP: A New Approach to Mapping Reservoir Flow and Permeability; with Drs. E. Wallin, E. Gasperikova, and Frank Morrison.

Evaluation of Geothermal Resource Potential of DOD Lands at Pohakuloa Using Magnetotelluric and Audiomagnetotelluric Surveys; with Dr. E. Wallin and B. Lienert

Magnetotelluric and Audiomagnetotelluric Surveys of Department of Hawaiian Home Lands, Humu'ula Hawaii; with Drs. E. Wallin, B. Lienert, and H. Pierce.

#### **Publications**

#### Published:

Revil, A., Y Qi, A Ghorbani, M Gresse, D M Thomas, 2021, Induced polarization of volcanic rocks. 5. Imaging the temperature field of shield volcanoes, Geophysical Journal International, V. 225, No. 3, Pages 1492–1509, https://doi.org/10.1093/gji/ggab039

- Attias, E., D.M. Thomas, D. Sherman, K. Ismail, and S. Constable, 2020, Marine electrical imaging reveals novel freshwater, Sci. Adv., Nov 25;6(48):eabd4866, doi: 10.1126/sciadv.abd4866.
- Calvin, W.M., N.C. Lautze, J. Moore, D.M. Thomas, E. Haskins, and B.P. Rasmussen, 2020, Petrographic and Spectral Study of Hydrothermal Mineralization in Drill Core from Hawaii: A potential analogue to alteration in the Martian subsurface. American Mineralogist. Invited contribution to special issue, v. 105, no. 9, p. 1297-1305, doi: 10.2138/am-2020-7125.
- Pierdominici, S., J. Kuck, J.M. Millett, D.M. Thomas, D.A. Jerram, S. Planke, E. Haskins, N.C. Lautze, and O. Galland, 2020, Stress Field Interactions between Large Overlapping Shield Volcanoes: Borehole Breakout Evidence from the Big Island of Hawai'i, USA. Journal of Geophysical Research: Solid Earth, doi: 10.1029/2020JB019768.
- Jerram, D.A., J.M. Millett, J. Kuck, D.M. Thomas, S. Planke, E. Haskins, N.C. Lautze, and S. Pierdominici, 2019, Understanding volcanic facies in the subsurface: A combined core, wireline logging and image log data-set from the PTA2 and KMA1 boreholes, Big Island, Hawai'i, Scientific Drilling, v. 25, p. 15-33, doi: 10.5194/sd-25-15-2019.
- Revil, A. M. Le Breton, Q. Niu, E. Wallin, E. Haskins, and D.M. Thomas, 2017. Induced polarization of volcanic rocks 1. Surface versus quadrature conductivity, Geophysical Journal International, v. 208, n. 2, p. 826–844, doi: 10.1093/gji/ggw444.
- Revil, A., Mathieu Le Breton, Qifei Niu, Erin Wallin, Eric Haskins, and Donald M. Thomas, 2017. Induced polarization of volcanic rocks. 2. Influence of pore size and permeability, Geophysical Journal International, v. 208, n. 2, p. 814–825, doi: 10.1093/gji/ggw382.
- Lautze N., Thomas D., Hinz N., Apuzen-Ito G., Frazer N., Waller D. 2017, Play Fairway Analysis of Geothermal Resources across the State of Hawaii: 1. Geological, geophysical, and geochemical datasets, Geothermics 70: 376-392
- Ito G., Frazer N., Lautze N., Thomas D., Hinz N., Waller D., Whittier R., Wallin, E. 2017, Play Fairway Analysis of Geothermal Resources across the State of Hawaii: 2. Resource Probability Mapping, Geothermics 70: 393-405
- Lautze N., Thomas D., Waller D., Hinz N., Frazer N., Apuzen-Ito G., 2017, Play Fairway Analysis of Geothermal Resources across the State of Hawaii: 3. Use of Development Viability as one criteria to prioritize future exploration activities. Geothermics 70: 406-413
- Revil, Andre (Universite Savoie Mont-Blanc, Institut des Sciences de la Terre, Le Bourget du Lac, France); Le Breton, M.; Niu, Q.; Wallin, E.; Haskins, E.; Thomas, D. M. 2017, Induced polarization of volcanic rocks; 2, Influence of pore size and permeability Source: Geophysical Journal International, V. 208, pp. 814-825.
- Revil, A., Le Breton, M., Niu, Q., Wallin, E., Haskins, E., Thomas, D.M., 2017, Induced polarization of volcanic rocks 1. Surface versus quadrature conductivity, Geophysical

- Journal International, v 208, n 2, p 826-844.
- Pierce, H.A. and Thomas, D.M., 2009, Magnetotelluric and Audiomagnetotelluric Groundwater Survey Along the Humu'ula Portion of Saddle Road Near and Around the Pohakuloa Training Area, Hawaii. U.S. Geol. Survey Open File Report 2009-1135, 164 pp.
- Stolper, E.M., D.J. DePaolo, and D. M. Thomas, 2009, Deep Drilling into a Mantle Plume Volcano: The Hawaii Scientific Drilling Project. Scientific Drilling Journal, No.7, pp. 4-14.
- Edwards, H. K., Tripp, D., Castile, T., Bevens, D., **Thomas, D.**, 2007 Software Engineering Projects for Public Safety Modeling Lava Flows on the Big Island. Proceedings of the 2007 Conference on Software Engineering Research and Practice. Las Vegas, Nevada, United States. CSREA Press. ISBN 1-60132-033-7. Pages 159-165. June 2007.
- Edwards, K.E., Puckett, R., **Thomas**, D., 2005, Updating Scientific Legacy Systems to Bridge the Digital Divide: A Case Study. Proceedings of the 2005 Conference on Software Engineering Research and Practice. Las Vegas, Nevada, United States.
- D.J. DePaolo. E. Stolper, **D. Thomas**, 2001, Deep Drilling into a Hawaiian Volcano; The Hawaiian Scientific Drilling Project EOS, Transactions, AGU, 82, 154–155.
- Thomas, D.M., 1998, Geothermal Resources, Invited contribution to <u>Atlas of Hawaii</u>, University of Hawaii Press, Honolulu, HI, pp. 47-48.
- Conrad, M.E., **D.M. Thomas**, S. Flexser, and T.W. Vanneman, 1997, Fluid flow and water-rock interaction in the East Rift Zone of Kilauea Volcano, Hawaii, J. Geophys. Res., v. 102, no. B7, pp. 15,021-15,037.
- Guillou, H., L. Turpin, F. Garnier, S. Charbit, **D.M. Thomas**, 1997, Unspiked K-Ar dating of Pleistocene tholeitic basalts from the deep core SOH-4, Kilauea, Hawaii, Chemical Geology, 140 (1-2), p. 81-88.
- Garnier, F., E. Herrero-Bervera, C. Laj, H. Guillou, C. Kissel, **D.M. Thomas**, 1996, Geomagnetic field intensity over the last 42,000 years from core SOH-4, Big Island, Hawaii; Journal of Geophysical Research, B, Solid Earth and Planets, 101 (1), p. 585-600.
- Stolper, E.M, D.J. DePaolo, and **D.M. Thomas**, 1996, Introduction to special section: Hawaii Scientific Drilling Project, J. Geophys Res., V. 101, No. B5, pp. 11,593-11,598.
- DePaolo, D. J., Stolper, E., Thomas, D., Albarede, Francis, Chadwick, O., Clague, D.,
  Feigenson, M. D., Frey, F. A., Garcia, M. O., Hofmann, A. W., Ingram, B. L., Kennedy, B.
  M., Kirschvink, J., Kurz, M. D., Laj, Carlo, Lockwood, J. P., Ludwig, K. R., McEvilly, T. V.,
  Moberly, R., Moore, G. F., Moore, J. C., Morin, R., Paillet, F., Renne, P., Rhodes, M.,
  Tatsumoto, M., Taylor, H., Walker, G., Wilkins, R., 1996, Hawaii Scientific Drilling Project;
  summary of preliminary results, GSA Today, 6 (8), p. 1-8.

- Paillet F., and **D.M. Thomas**, 1996, Hydrogeology of the KP-1 Borehole, Part I: Hydraulic conditions adjacent to the well bore, J. Geophys Res., V. 101, No. B5, pp. 11,675-11,682.
- Thomas, D.M., F. Paillet and M. Conrad, 1996, Hydrogeology of the KP-1 Borehole, Part II: Fluid geochemistry and regional flow patterns, J. Geophys Res., V. 101, No. B5, pp. 11,683-11,694.
- Garnier, F., E. Herrero-Bevera, C. Laj, H. Guillou, C. Kissel, and **D.M. Thomas**, 1996, Geomagnetic field intensity over the last 42,000 years obtained from core SOH-4, Big Island, Hawaii, J. Geophys Res., V. 101, No. B1, pp. 585-600.
- C. Laj, F. Garnier, E. Herrero-Bevera, C. Kissel, and **D.M. Thomas**, 1996, Preliminary determinations of the geomagnetic field intensity for the last 450 kyr from Hawaii Scientific Drilling Project core, Big Island, Hawaii, J. Geophys Res., V. 101, No. B5, pp. 11,625-11,632.
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- Chen, C., R.E. Green, and **D.M. Thomas**, Model LEACHV for gas transport in unsaturated soil (User's manual)
- Chen, C. and **D.M. Thomas**, 1994, Analysis of volatile phase transport using natural radon gas as a tracer, Jour. Env. Quality, v. 23 no. 1, pp. 173-179.
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1991 to 1996	Hawaii Institute of Geophysics and Planetology; Graduate Student and Research Assistant
1970 to 1990	U.S. Navy, Submarine Force; Instrument Technician and Auxiliary Electrical Systems Manager

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Statewide nearshore sewage pollution study using nitrogen and nitrogen isotopes as tracers of wastewater, a Hawaii State Legislature mandated study. A collaboration between UH Marine Botany Program, Water Resources Research Center, and Hawaii Department of Health, Safe Drinking Water and Clean Water Branches.

Investigation of groundwater flow paths in southeast and south-central Oahu using general and isotope chemistry of groundwater as tracers. A collaboration between Hawaii Department of Health, Safe Drinking Water Branch and Water Resources Research Center.

An evaluation of the fluid transport characteristics of the lavas in the Red Hill area of Oahu, Hawaii. A collaboration between the Hawaii Department of Health, Safe Drinking Water and Hazard Evaluation and Emergency Response Branches; and the University of Hawaii, – Dept. of Geology and Geophysics.

#### **PUBLICATIONS:**

- Dores, D., Glenn, C.R., Guiseppe, T., **Whittier**, **R.B.**, and Popp, B.N. In Press. Implications for groundwater recharge from stable isotopic composition of precipitation in Hawai'i during the 2017-2018 La Niña. Hydrological Processes
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#### **CONFERENCE PRESENTATIONS:**

#### 2018 Pacific Water Conference

Honolulu, Oahu, Hawaii - February, 2018

R. Whittier - Using Geochemistry to Evaluate Groundwater Flow Paths

#### 2018 Hawaii Waterworks Association Conference

Poipu, Kauai, Hawaii - November, 2018

**R. Whittier** - Source Water Assessments: Challenges in Assessing the Contamination Risk to Drinking Water

#### 2017 Pacific Water Conference

Honolulu, Oahu, Hawaii - February, 2017

R. Whittier and J. Delevaux - Linking Groundwater to Coral Reef Management

### 2016 Hawaii Water Works Association/Hawaii Rural Water Association Conference

Kihei, Maui, Hawaii - November, 2016

R. Whittier and M. Dau - Using stable isotopes to investigate nitrate contamination

#### 2016 Pacific Water Conference

Honolulu, Oahu, Hawaii - February, 2016

R. Whittier - Wastewater meets groundwater and beyond

#### 2015 Pacific Water Conference

Honolulu, Oahu, Hawaii - February, 2015

**R. Whittier**, D. Thomas, J. Fackrell, P. Eyre – Merging isotope chemistry with numerical modeling to investigate groundwater zones of contribution

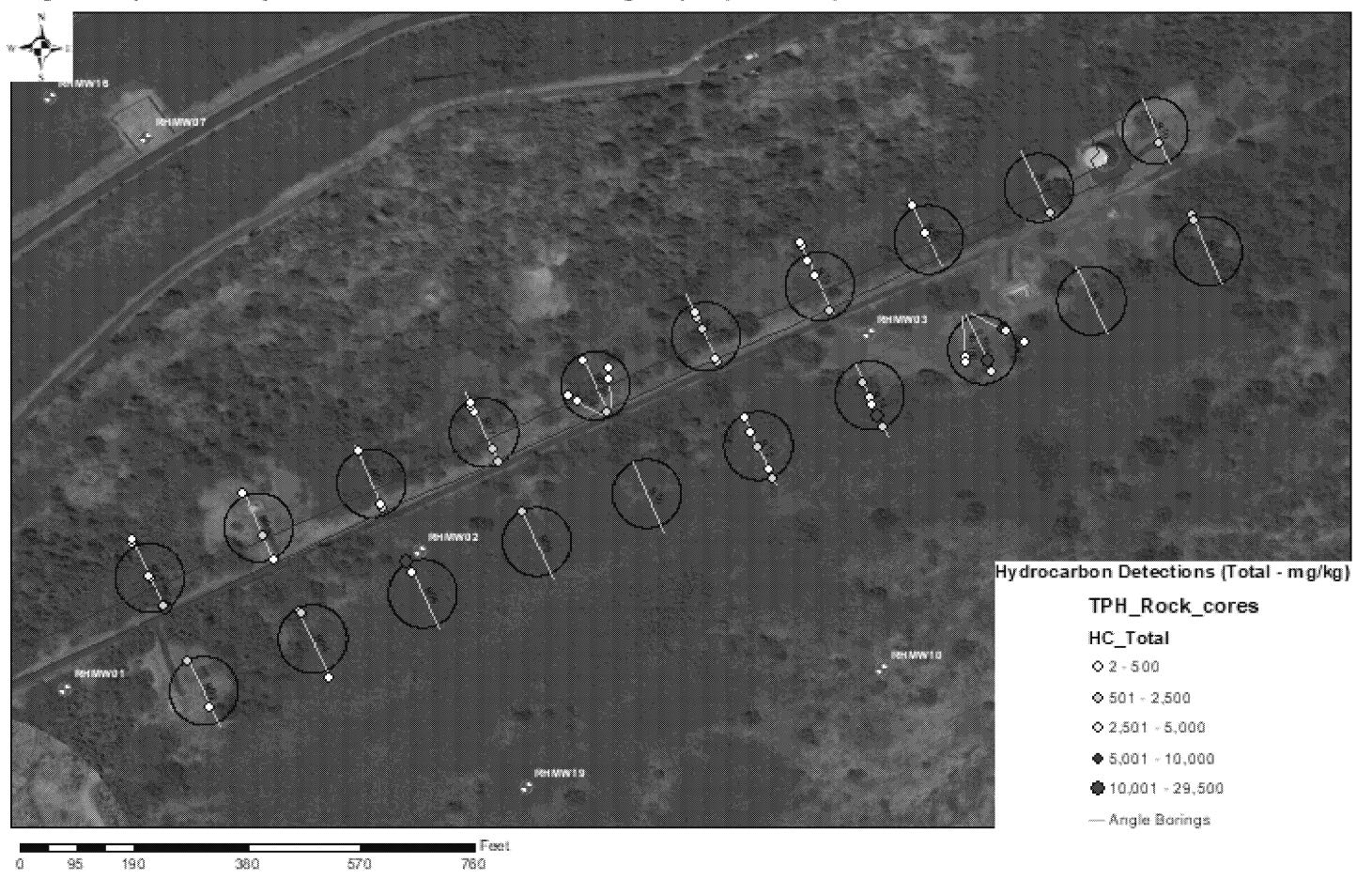
#### 2014 Water Reuse Conference

Honolulu, Oahu, Hawaii - November, 2014

R. Whittier - Assessing the leachability of recycled water contaminants

# **REVIEW FIGURES**

Figure 1: Reported Total Hydrocarbon Detections from Slant Boring Samples (1998 - 2002)



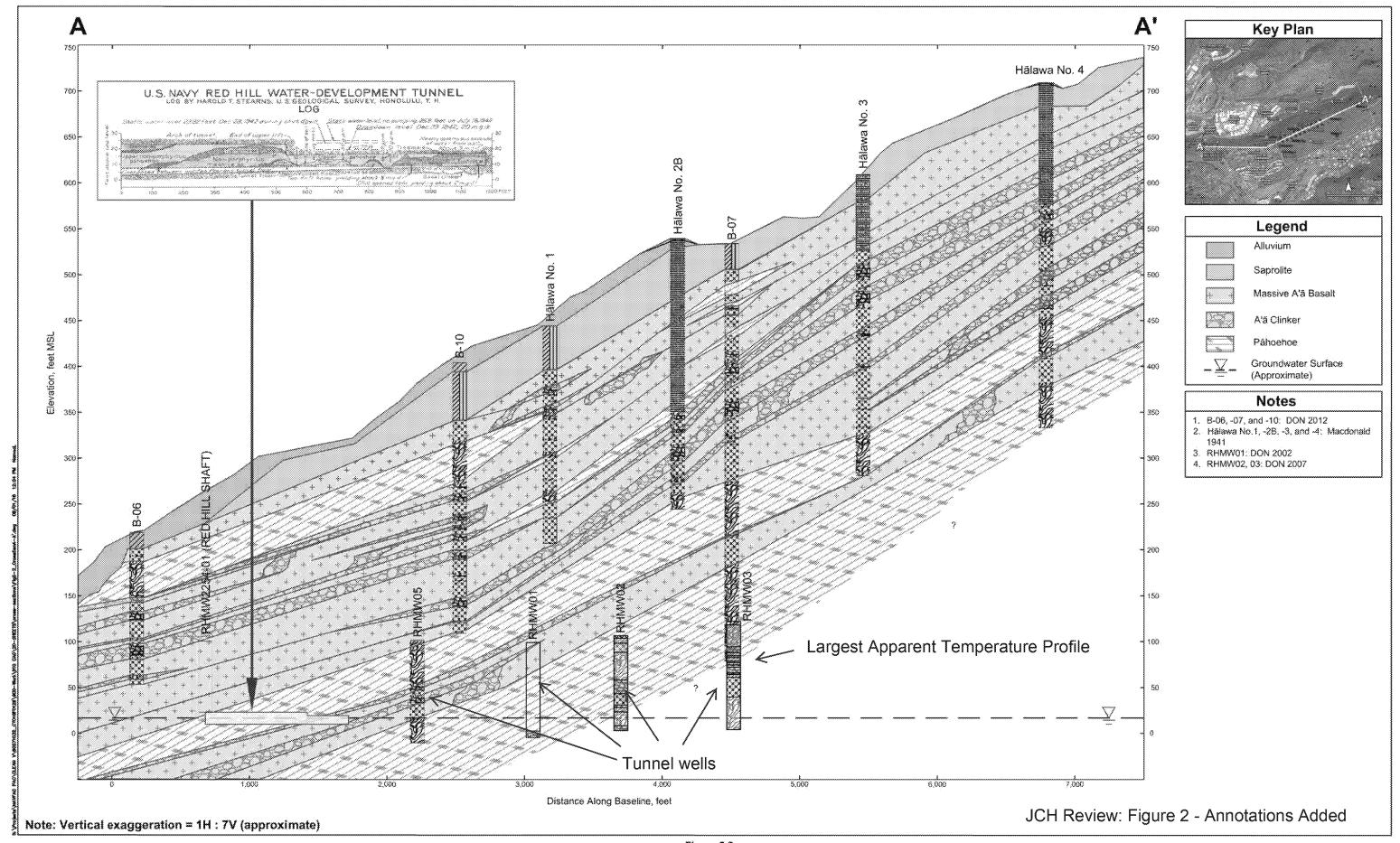
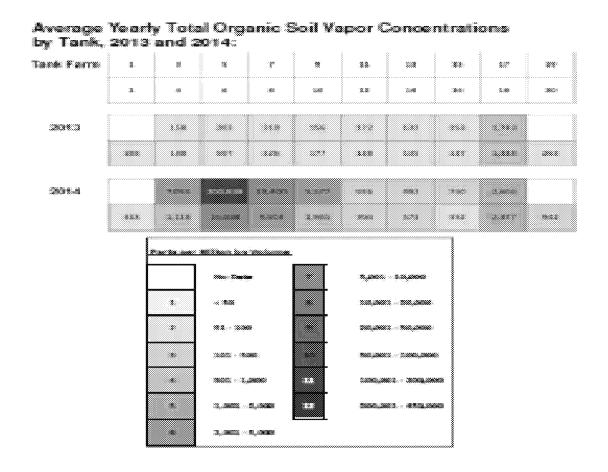


Figure 5-2
Cross Section A-A'
Conceptual Site Model
Investigation and Remediation of Releases and Groundwater Protection and Evaluation
Red Hill Bulk Fuel Storage Facility, JBPHH, O'ahu, Hawai'i



Prior to Tank 5 release

After Tank 5 release

Figure 3, Schematic showing widespread vapor concentration increaes following the 2014 Tank 5 release. Source, Red Hill CSM, June 2019.

Annotations added.

## NAVY CONCEPTUAL SITE MODEL – EXECUTIVE SUMMARY

Full public domain text may be found at: <a href="https://www.epa.gov/sites/production/files/2019-07/documents/red-hill-conceptual-site-model-20190630-redacted.pdf">https://www.epa.gov/sites/production/files/2019-07/documents/red-hill-conceptual-site-model-20190630-redacted.pdf</a>

# Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility JOINT BASE PEARL HARBOR-HICKAM, O'AHU, HAWAI'I

Administrative Order on Consent in the Matter of Red Hill Bulk Fuel Storage Facility, EPA Docket Number RCRA 7003-R9-2015-01 and DOH Docket Number 15-UST-EA-01, Attachment A, Statement of Work Section 6.2, Section 7.1.2, Section 7.2.2, and Section 7.3.2

June 30, 2019 Revision 01



Comprehensive Long-Term Environmental Action Navy Contract Number N62742-17-D-1800, CTO18F0126

#### **EXECUTIVE SUMMARY**

- 2 This Conceptual Site Model (CSM) document is an iterative (evolving) representation of the Red Hill
- area based on all data obtained to date. The CSM thus provides a basis for evaluating groundwater 3
- 4 flow, behavior of contaminants in the environment, contaminant transport pathways, and the potential
- 5 for exposure of human receptors to potentially impacted drinking water in support of the Investigation
- 6 and Remediation of Petroleum Product Releases and Groundwater Protection and Evaluation project,
- 7 at Red Hill Bulk Fuel Storage Facility ("the Facility"), Joint Base Pearl Harbor-Hickam (JBPHH),
- Hawai'i. The Facility is owned by the United States (U.S.) Navy (DON; "Navy") and operated by 8
- 9 Defense Logistics Agency (DLA).

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- 10 This document has been prepared under Statement of Work Sections 6 and 7 of the Administrative
- Order on Consent (AOC) In the Matter of Red Hill Bulk Fuel Storage Facility (EPA Docket No: 11
- 12 RCRA 7003-R9-2015-01; DOH Docket No: 15-UST-EA-01) (EPA Region 9 and DOH 2015). The
- 13 AOC was issued by the U.S. Environmental Protection Agency (EPA) Region 9 and State of Hawai'i
- 14 Department of Health (DOH) (EPA Region 9 and DOH 2015) to the Navy/DLA in response to a release
- 15 of an estimated 27,000 gallons of Jet Fuel Propellant (JP)-8 from one of the Facility's underground
- 16
- fuel storage tanks (Tank 5) that was confirmed and reported to DOH on January 23, 2014. The tanks
- 17 are located above a major groundwater aquifer, which is used to feed both Navy and City and County
- 18 of Honolulu drinking water supply wells and shafts.
- 19 The initial CSM (Revision 00) (DON 2018g) was developed in accordance with the CSM Development
- 20 and Update Plan (DON 2017i) to identify and evaluate the site-specific characteristics and processes
- 21 that control the fate and transport of fuel (light non-aqueous-phase liquid [LNAPL]) and its constituent
- chemicals (petroleum hydrocarbons) from the source of a release (underground fuel storage tank[s] at 22
- 23 the Facility), through the vadose and saturated zones, and on to potential receptors (e.g., residential
- 24 receptors exposed via the drinking water pathway). The CSM is an evolving tool that will continue to
- 25 be updated as new information becomes available.
- 26 Regulatory Agency Comments. The Regulatory Agencies identified their top ten concerns with
- 27 previously submitted reports and presentations during an August 14, 2018 Technical Working Group
- meeting and further summarized those concerns in their October 29, 2018 letter to the Navy approving 28
- 29 a revised schedule for forthcoming deliverables under AOC Statement of Work Sections 6 and 7. Since
- 30 identification of those ten concerns, the Navy has been completing additional analyses and presenting 31
- results to the Regulatory Agencies to achieve alignment on these concerns. Some alignment has been
- 32 achieved, while other technical issues remain unresolved. A summary of the status of each of the ten
- concerns, as well as the Navy's position regarding the concern, is provided in Appendix J. A primary 33
- 34 goal of this CSM Revision 01 is to address the issues identified in these comments to the extent
- 35 possible. This CSM Revision 01 incorporates additional data and evaluations accordingly.
- 36 Key Findings. Key findings from recently completed studies, field work, and computer simulations
- 37 include:

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- Long-term monitoring (LTM) and associated studies do not indicate that the 2014 release from
- 39 Tank 5 impacted groundwater at Red Hill Shaft based on evaluation of multiple lines of
- 40 evidence (LOEs).
- 41 Based on thermal natural source-zone depletion (NSZD) studies, LTM, and other studies indicate that LNAPL is retained in the pore spaces of the rock within approximately 30 feet 42
- 43 (ft) beneath the tanks and has not reached groundwater.

- Geologic information about the formation of lava tubes indicates that these will not act as preferential pathways for contaminants to flow between the Red Hill Facility and City and County of Honolulu Board of Water Supply (BWS) water supply wells or Red Hill Shaft.
  - Seismic studies and borings (borings in South Hālawa only) indicate that extensive saprolite zones exist beneath stream valleys on both sides of Red Hill (including South Hālawa Stream and Moanalua Valley), and that these extend significantly below the water table. Where that occurs, they act as a barrier to groundwater flow and contaminant migration.
  - While the heterogeneous geology beneath Red Hill results in locally variable hydraulic gradients, the overall groundwater flow direction is southwestward from the tank area, and flow appears to be highly influenced by clinker zones that might provide preferential pathways to Red Hill Shaft.
  - Natural attenuation is occurring in both the unsaturated and saturated zones, and it acts to degrade petroleum contaminants in the environment.
  - Risk-based decision criteria (RBDC) have been developed that are protective of human health in regard to chemicals of potential concern (COPCs) that may potentially impact public water supplies.
  - COPCs detected in water development tunnel shafts have not exceeded the RBDC.
  - Data collected as part of recent synoptic water level studies assisted with the development of
    aquifer hydraulic property estimates and evaluation of groundwater flow conditions in the site
    area.
  - A transfer function-noise (TFN) analysis was completed using the recently collected synoptic water level data. The TFN analysis simulates the water level response to each hydraulic stress component (e.g., barometric pressure, pumping from shafts, tidal and other influences) through evaluation (convolution integration) of the hydraulic stress time series. The results of the TFN analysis indicate that pumping at Red Hill Shaft has the strongest influence on water level variability in the vicinity of Red Hill, relative to any other stresses evaluated. The TFN analysis allowed both development of step response functions (used to assist with groundwater model calibration) and estimation of aquifer hydraulic properties.
- CSM Modules. This document is organized into seven detailed modules that describe the site-specific data and information, or LOEs, used to develop the current version of the CSM and evaluate remaining uncertainties. These seven modules are summarized in Table ES-1, which identifies the LOEs to date, the remaining uncertainties, and the activities planned to help fill existing data gaps and help address the uncertainties.

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#### Table ES-1: Summary of CSM Modules

Conceptual Model

#### Module A: Physical Setting

The 144-acre underground fuel storage Facility is located in south-central Oʻahu approximately 2–3 miles east of Pearl Harbor, within the Red Hill ridge that divides South Hālawa Valley from Moanalua Valley on southwest flank of Oʻahu's Koʻolau Mountain Range. The Facility's twenty 250-ft-tall,12.5-million-gallon fuel storage tanks store and supply fuel for military operations in Hawai'i and throughout the Pacific. The tank bottoms are situated approximately 100–130 ft above an underlying basal aquifer that is a major municipal and military drinking water source and is considered an irreplaceable resource with a high vulnerability to contamination.

Below the surface soil and saprolite of Red Hill ridge, geologic formations consist largely of basalt with varying layers of materials exhibiting high and low permeability and containing occasional voids. In the surrounding valleys, sedimentary deposits are underlain by weathered basalt (saprolite) and unweathered basalt.

In the vicinity of Red Hill, the basal aquifer water table lies at approximately 20 ft above mean sea level, and regionally groundwater flows toward Pearl Harbor (Mauka to Makai), although potential exists for variability in localized flow directions depending on geologic formations and other factors.

#### Module B: Facility Construction and Operations

The Facility's 20 fuel storage tanks were field-constructed of steel-lined concrete in the early 1940s. They are connected to a fuel pumping station at Pearl Harbor via a tunnel system. Kerosene-based jet fuels stored at the Facility have included JP-5, JP-8, and NATO-grade F-24; the tanks currently contain kerosene-based JP-5 and F-24, and F-76 Diesel Fuel-Marine.

#### Module C: LNAPL Release Source Zone

During Tank 5 refilling operations following a routine 3-year inspection and refurbishment process conducted every 20 years, a release of approximately 27,000 gallons of JP-8 was confirmed and reported to DOH in writing on January 23, 2014. During that month, a fuel hydrocarbon seep confirmed to be JP-8 was observed on a tunnel wall below Tank 5, and soil vapor monitoring points installed beneath the tank exhibited a sharp increase in hydrocarbon vapor concentrations. Potential migration pathways include gaps between the tank's steel lining and inner side of its concrete shell, and cracks in the concrete shell into higher-permeability rock surrounding the concrete.

Subsequent analysis indicated the cause of the release to be defective workmanship in welding by the tank refurbishment contractor, poor inspection, and ineffective quality control.

#### Module D: Vadose Zone

The Facility tanks are surrounded by rock in the vadose (i.e., unsaturated) zone, which consists primarily of basalt flows in complex, alternating layers. These heterogeneous layers vary from extremely high to extremely low permeability, with a corresponding varying ability to transmit and hold LNAPL depending on the layer's rock type and micro-pore structure (i.e., high ability in high-permeability a'ā and thin pāhoehoe flows; low ability in massive a'ā and massive pāhoehoe flows; limited transmissivity but high holding capacity in a'ā clinker zones). Geologic and water saturation characteristics in the rock surrounding the tanks could cause LNAPL to spread as it moves through the rock. As LNAPL moves through the larger pore spaces, some of it could be trapped in poorly connected fractures and blocked by surface tension and capillary forces of moisture, especially water held in the smaller pores.

Hawaiian volcanic rocks vary in porosity and permeability depending on the emplacement process, lava type, genesis, flow thickness, flow rate, extent, cooling rate, and weathering. Permeability is typically highest in the relatively thick, unweathered rubbly a'ā clinker zones and intensely fractured zones or lava tubes of pāhoehoe flows. Permeability is much lower in the interior portions of massive flows, weathered interflows, intrusive rocks (dikes/sills), ash beds, and weathered rocks (saprolite)/soil horizons, which can impede vertical flow and horizontally flow across valleys. Generally, the bulk vertical permeability of the basalt is orders of magnitude lower than the bulk horizontal permeability. Horizontal permeability is higher in the direction that the lava flowed.

Conceptual Model

#### Module E: Saturated Zone

Groundwater flow and solute transport are controlled by hydraulic conditions (e.g., gradients) and physical properties of the hydrogeologic units (HGUs), including hydraulic conductivity, effective porosity, specific yield, specific storage, anisotropy, and dispersivity.

Fresh groundwater inflow originates as deep infiltration of precipitation and seepage from surface water features. According to the United States Geological Survey (USGS), estimates of recharge for O'ahu for recent conditions (2010 land cover and 1978–2007 rainfall) differ from predevelopment recharge values by only a few percent (Izuka et al. 2018). Spatial distribution of recharge mimics the orographic rainfall pattern—recharge is highest on windward slopes and mountain peaks below the top of the trade-wind inversion.

Groundwater outflow includes withdrawals from wells and natural groundwater discharge to springs, streams, wetlands, and submarine seeps. Data collected by the USGS for groundwater levels, saltwater/freshwater interface, spring flow, and stream base-flow indicate an overall reduction in aquifer storage for most areas where groundwater has been extracted; this has caused groundwater levels to decline (Izuka et al. 2018).

Regional groundwater levels decrease from areas of recharge (mauka) to areas of discharge (makai). Locally, water level gradients are extremely low and are influenced by geologic conditions as well as by variability in local pumping stresses from water development shafts and wells.

#### Module F: Fate and Transport of LNAPL and Dissolved COPCs in Groundwater

Attenuation studies, in the vadose zone as NSZD and in the dissolved groundwater plume as monitored natural attenuation (MNA), provide strong evidence of biodegradation. Occurrence of LNAPL is primarily limited to a depth of 30 ft beneath monitoring wells RHMW02 and RHMW03 and is being biodegraded based on thermal, soil vapor, and carbon trap studies. Attenuation of dissolved-plume COPCs in the saturated zone limits the extent of the existing small dissolved plume before reaching Red Hill Shaft under present conditions and within the context of historical releases. Spatial and temporal trends in COPCs, NAP data, and fuel studies provide strong evidence that active and robust attenuation processes are responsible for COPC degradation within groundwater plume under the tank farm.

Profiles of total petroleum hydrocarbons—diesel-range organics (TPH-d) from site data are consistent with soluble components of jet fuel. The available chromatograms from RHMW02 groundwater samples are all consistent with chromatograms for biodegraded kerosene-type fuels (e.g., JP-5 and JP-8). Petroleum fuels are composed primarily of hydrocarbons (nonpolar) that have distinctive chromatographic profiles. The majority of the fuel is not water soluble, and the chromatographic profiles are useful in distinguishing LNAPL from soluble fuel components and biodegraded material, Polar compounds are present in the groundwater, indicating ongoing biodegradation.

#### Module G: Exposure Model

Historical releases (prior to 2005) are considered the main source of impacts to groundwater at the Facility. Other releases (e.g., spills or leaks in the fuel system) may have occurred or may occur in the future. Potentially contaminated media are unconsolidated materials, volcanic rock within the tunnels, soil/rock vapor within the tunnels, tunnel air, groundwater beneath the Facility, and offsite surface water where groundwater may discharge. Human receptors that may contact onsite or offsite Facility-impacted media are Facility occupational workers, construction workers, and visitors, and offsite residents. Among the potentially complete exposure pathways identified, the primary one is offsite residents using tap water sourced from the Red Hill Shaft water supply well. These receptors could be exposed to chemicals in tap water via direct ingestion and dermal contact, and via inhalation while showering/bathing. Exposure by ecological receptors is considered incomplete or insignificant.

- 1 Overall, the current CSM indicates that LNAPL released from Red Hill fuel storage tanks has entered
- the vadose zone at various areas and times beneath Red Hill. Soil vapor monitoring data from beneath
- 3 the tanks indicate that no significant releases have occurred since the monitoring program was initiated
- 4 in 2008 with the exception of the January 2014 Tank 5 release.
- 5 Conceptual LNAPL Behavior. LNAPL entering the vadose zone encounters a complex geology in
- 6 the surrounding volcanic layers that vary significantly in their permeability and overall geometry.
- 7 Consequently, LNAPL will migrate laterally through high-permeability zones underlain by low-
- 8 permeability layers. Vertical migration can occur through clinker bridges, and highly fractured zones
- 9 within flows. As LNAPL moves through the pore spaces, some of it will be trapped in poorly connected
- intraflow fractures, voids, and pores. The LNAPL is expected to preferentially migrate along the
- 11 predominant dip direction to the south-southwest. Once the LNAPL encounters the water table, its
- vertical migration potential is minimized due to the density difference between LNAPL and water.
- 13 Soluble components (monitored by analyzing groundwater samples for COPCs) would enter the

- 1 groundwater through either dissolution from LNAPL in the vadose zone due to infiltrating water or
- 2 through dissolution of LNAPL in the saturated zone close to the water table. Currently, no LNAPL
- has been measured in the water table monitoring wells. However, analytical data indicate the possible
- 4 presence of LNAPL upgradient of Red Hill monitoring well RHMW02. The thermal profile study
- 5 conducted in October 2017 shows evidence that residual LNAPL is primarily limited to a depth of
- 6 30 ft beneath the top of wells RHMW02 and RHMW03 (inside the lower access tunnel) and is being
- 7 biodegraded.

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- 8 Observed Behavior of COPCs. General transport of COPCs in the dissolved plume is expected to be
- 9 in the southwest direction toward Red Hill Shaft, based on regional groundwater flow conditions,
- 10 previous groundwater modeling by other researchers, ongoing groundwater modeling evaluations
- being conducted by the Navy, and the influence of Red Hill Shaft on groundwater conditions identified
- by a TFN analysis. The TFN analysis showed that pumping Red Hill Shaft was the primary factor
- influencing variability of water levels at Red Hill. Migration to the southeast and northwest is expected
- 14 to be limited by the extent of lower-permeability materials (valley fill and saprolite) extending below
- the water table in the valleys bounding the Facility. Attenuation of COPCs in the dissolved plume in
- the saturated zone limits the extent of the existing dissolved plume before reaching Red Hill Shaft
- under present conditions and within the context of historical releases.
- 18 Uncertainties. CSM Revision 00 (July 27, 2018) identified uncertainties that have been partly or fully
- 19 addressed by evaluation of new data that is documented in this CSM Revision 01. The primary
- 20 uncertainties identified in CSM Revision 01 are:
- The nature of subsurface geology in North and South Hālawa Valleys
- Groundwater levels and hydraulic gradients in the site vicinity
- Extent of near-surface groundwater on the north side of Red Hill and the adjacent South Hālawa Valley floor
- Migration and retention of LNAPL following a release
  - Groundwater flow directions and rates in the groundwater model domain
  - Subsurface geologic features that may act as preferred groundwater flow pathways or barriers (e.g., lava tubes, clicker beds)
    - Spatial distribution of COPC concentrations dissolved in groundwater between the Facility and water supply wells in North Hālawa Valley and Moanalua Valley
- Ongoing new data collection, evaluations, and proposed activities to address remaining uncertainties include the following:
  - Groundwater levels and flow: Incorporate in the modeling effort the results of Red Hill monitoring water level measurements from the progressively expanding monitoring well network. Assess groundwater level data from additional monitoring wells and test borings (RHMW11, RHTB01, and RHMW14) and augment with data from future wells currently being installed (RHMW12, RHMW13) at Red Hill and in North and South Hālawa Valleys. Continue to collect groundwater level data to represent both non-pumping conditions and various combinations of pumping of water supply wells in the area. Collect groundwater level measurements from intervals deeper below the water table.
- Subsurface geology: Collect additional hydrogeologic data and prepared detailed borehole geologic logs of deep borings in areas beneath North and South Hālawa Valleys.

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- *COPC concentrations:* Continue to monitor for COPCs in the progressively expanding monitoring well network.
  - Biodegradation: Evaluate recently collected thermal profiling data from key monitoring wells both in the tank area and outside and adjacent to the tank area for evidence of biodegradation. Continue collection and evaluation of natural attenuation parameter (NAP) data (e.g., dissolved oxygen and dissolved methane in groundwater and in the soil vapor monitoring points).
  - LNAPL migration and retention: Inspect new cores for presence of LNAPL. Collect petrographic data on select cores from proposed new monitoring well RHMW01R, located within the tank farm.

# ATTACHMENT 1

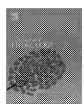
"Direct aerobic NSZD of a basalt vadose zone LNAPL source in Hawaii"; Journal of Contaminant Hydrology, Volume 235, November 2020

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## Journal of Contaminant Hydrology

journal homepage: www.elsevier.com/locate/jconhyd



#### Direct aerobic NSZD of a basalt vadose zone LNAPL source in Hawaii



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#### ARTICLE INFO

#### Keywords: Aerobic Biodegradation LNAPL Basalt NSZD

#### ABSTRACT

In recent years, a number of methods have been used to measure the biodegradation of petroleum light non-aqueous phase liquids (LNAPL) at petroleum release sites, a process known as natural source zone depletion (NSZD). Most commonly, NSZD rates have been measured at sites with unconsolidated geology and relatively shallow groundwater (< 50 ft. bgs, < 15 m bgs). For this study, we have used two methods (1. carbon dioxide flux measured using carbon traps and 2. heat flux based on subsurface temperature gradients) to measure NSZD rates at a petroleum release site in Hawaii with basalt geology and deep groundwater (> 300 ft. bgs, > 100 m bgs). Both methods documented the occurrence of NSZD at the facility and the two methods yield estimates of the NSZD rate that agreed within a factor of 2 (4600 to 7400 gal/yr; 17,000 to 28,000 L/yr for the flux method and 8600 to 13,000 gal/yr; 33,000 to 49,000 L/yr for the temperature method). Soil gas samples collected directly above the water table and at shallower depths within the vadose zone indicated aerobic conditions throughout the vadose zone (oxygen > 13%) and no detectable methane. These results indicate that NSZD occurs at this site through the direct aerobic biodegradation of LNAPL rather than the two-step process of anaerobic methanogenesis followed by methane oxidation at a shallow depth interval documented at other sites.

#### 1. Introduction

Thousands of sites around the world are affected by historical releases of light non-aqueous phase liquids (LNAPL) such as crude oil, refined fuels, lubricants, and heating oil. Traditionally, active treatment technologies (e.g., hydraulic recovery, air sparging, multi-phase extraction, soil vapor extraction [SVE], etc.) have been applied as common remediation approaches for most LNAPL sites (US RPA, 2005; ITRC, 2009; McHugh et al., 2014). Except for complete excavation, none of these in-situ remediation technologies has been demonstrated to completely remove all the LNAPL within the treatment zone (Sookhak Lari et al., 2020). In recent years, however, there has been an increasing recognition that bacterial degradation of petroleum constituents within LNAPL source areas is an important contributor to LNAPL removal, a process known as natural source zone depletion (NSZD, Garg et al., 2017; Sookhak Lari et al., 2019).

A number of methods have been developed to quantify NSZD rates based on tracking the consumption of oxygen and/or the generation of carbon dioxide (CO<sub>2</sub>) associated with biological degradation of petroleum (API, 2017; CRC Care, 2018). These include measurement of  $CO_2$ 

and oxygen concentration gradients (ITRC, 2009) and the use of dynamic closed chambers (Sibota et al., 2011) and passive  $\mathrm{CO}_2$  traps (McCoy et al., 2015) to measure  $\mathrm{CO}_2$  flux at the ground surface above LNAPL source areas. All of these methods utilize the measured flux of oxygen into the LNAPL source area or flux of  $\mathrm{CO}_2$  out of the LNAPL source area to determine the LNAPL degradation rate (i.e., the amount of LNAPL degradation required to account for the measured amount of oxygen consumption or  $\mathrm{CO}_2$  production).

More recently, researchers have developed and demonstrated a temperature-based monitoring method to measure NSZD rates for petroleum LNAPL source areas (Warren and Bekins, 2015; Askarani et al., 2018; Saie et al., 2014). This approach utilizes measurement of the heat generated from biological LNAPL degradation to quantify the LNAPL degradation rate. For this approach i) vertical temperature profiles are collected, recording the soil temperature from ground surface down through the LNAPL source area, ii) this temperature profile is used to determine the heat flux away from the biological reaction zone, and iii) this heat flux is used to calculate the amount of petroleum being degraded (i.e., the volume of petroleum per unit area per unit time required to account for the amount of heat being generated).

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These flux and temperature NSZD measurement methods have shown LNAPL biodegradation rates of 100 s to 1000 s of gallons of LNAPL per acre per year (roughly 1000 s to 10,000 s of kilograms per hectare per year) (Garg et al., 2017) at almost every site where NSZD rates were measured. In addition, these LNAPL removal rates commonly exceed what can be achieved with long-term active LNAPL recovery remedies. As a result, NSZD is gaining broad acceptance as a viable and cost-effective remedy for mature LNAPL releases (Sale et al., 2018a, 2018b). However, to-date, NSZD rates have been reported in the literature at only a few dozen sites in a limited range of environmental settings: typically sites with unconsolidated soils, relatively shallow groundwater (< 50 ft. bgs), and permeable surface cover (i.e., no pavement or buildings). At these sites, NSZD typically occurs as a two-step process: i) anaerobic methanogenic degradation of petroleum constituents within the LNAPL source area and ii) methane oxidation in the vadose zone above the LNAPL source area at the depth interval where upward-diffusing methane meets downward-diffusing oxygen from the ground surface. Because the methane oxidation is the primary heat source for this two-step process, the interval of heat generation corresponds to this methane oxidation zone rather than the depth of the LNAPL source area (Warren and Bekins, 2015). For LNAPLs with a significant volatile fraction, oxidation of VOCs in the vadose zone may also contribute to NSZD (Sookhak Lari et al., 2019).

In this paper, we demonstrate the measurement of NSZD rates for an LNAPL source area at the Red Hill Bulk Fuel Storage Facility (RHBFSF) on Oahu, Hawaii characterized by a high-permeability basalt vadose zone greater than 300 ft. thick. A weathered basalt (saprolite) layer overlies the facility, minimizing recharge from rainfall. To our knowledge, this is one of only a few sites where NSZD rates have been measured in a consolidated (rock) geologic setting and the first example of NSZD that appears attributable to direct aerobic degradation within the LNAPL source area.

#### 2. Methods

The study site consists of 20 very large (12.5 million gallon/47 million L) steel-lined, reinforced concrete (two-and-a-half to four foot thick) underground storage tanks installed within a thick basalt vadose zone such that the base of the tanks is approximately 120 ft. (40 m) above the groundwater table. Each tank is approximately 250-ft (75 m) tall and 100-ft (30 m) in diameter. The tanks have been in service since the mid 1940s, and 18 of the tanks remain in service. The tanks have been utilized primarily for storage of middle-distillate fuels (Jet Fuels, Marine Diesel Fuels) with more limited past storage of gasoline-range fuel. The tanks are arranged in two rows of ten tanks each running from ESE to WNW. A lower access tunnel runs between the two rows of tanks just below the base of the tanks, and an upper access tunnel runs between the two rows of tanks at an elevation of approximately 180 ft. (55 m) above the bottom of the tanks (Fig. 1). In addition to providing access to the tanks for maintenance, the lower access tunnel provides access to 47 soil gas monitoring points (two to three points below each tank), three monitoring wells installed within the tank farm area, and one monitoring well installed downgradient of the tank farm area (Fig. 2). Additional monitoring wells outside the tank farm area used for this study are accessible from ground surface (Fig. 2). Aside from the access tunnels, the native rock around the tanks is largely undisturbed.

The basalt is highly permeable relative to most contaminated sites in unconsolidated settings. The high permeability components of the basalt include massive a'ā (thick/chunky lava flows), clinker zones (layers of gravel-like lava fragments between a'ā layers) described as "high permeability material analogous to coarse, clean, gravel" and pāhoehoe (thin/smooth lava flows) that have "high intrinsic permeability similar to that of carbonate rocks" (Hant, 1996). Overall Hunt (1996) reports that when averaged over several lava-flow thicknesses, the lateral hydraulic conductivity of dike free lava flows such as found in the vicinity of Red Hill is about 500 to 5000 ft per day (0.18 to 1.8 cm/

s). This is about 23 to 230 times higher than the median hydraulic conductivity of 0.008 cm/s for 191 contaminated sand and gravel groundwater sites from Newell et al. (1990). Due to this high permeability, advective or diffusive air penetration into the unsaturated basalt is much more likely than for sites comprised of unconsolidated media.

Prior investigation results indicate historical petroleum fuel releases prior to 1988 of unknown volume from several tanks and one more recent release of 27,000 gal (100,000*L*) of jet fuel in 2014. Evidence of prior releases includes visible staining and detection of Total Petroleum Hydrocarbons (TPH) in rock cores collected from angled borings completed below the fuel tanks in the late 1990s and early 2000s documenting the presence of LNAPL within a depth interval of approximately 10 ft. to 30 ft. (3 to 10 m) below the bottom of the fuel tanks. These angled borings were later converted to soil gas monitoring points (Fig. 1). LNAPL has not been observed in groundwater (approximately 120 ft., 35 m below the bottom of the fuel tanks) in any of the monitoring wells.

The RHBFSF has implemented modern release prevention and release detection technologies. The purpose of this study was to better understand NSZD rates and processes for historical releases.

Three methods were applied to quantify NSZD rates for LNAPL associated with these prior releases: i) the passive  $\mathrm{CO}_2$  trap method with traps installed at the surface of the facility; ii) an adapted  $\mathrm{CO}_2$  trap method where  $\mathrm{CO}_2$  was measured in the exhaust from the ventilated Red Hill tunnel system; and iii) the temperature method. In addition, oxygen,  $\mathrm{CO}_2$ , and methane concentrations and differential pressure were measured at each below-tank soil gas point and monitoring well headspace.

#### 2.1. Carbon trap measurements

Carbon traps from E-Flux (Fort Collins, CO) were used to measure the flux of  $CO_2$  at the ground surface and through the two access tunnels. Flux at the ground surface was measured by deploying eight standard E-Flux carbon traps; two transect lines of four traps were deployed, each transverse to the rows of tanks resulting in two carbon traps north of the tanks, four traps above the tanks, and two traps south of the tanks. The surface traps were deployed for 14 days in the fall of 2017 (Fig. 3).

 ${\rm CO_2}$  flux within the two tunnels was measured using custom packed carbon trap cartridges from *E*-Flux. These cartridges were deployed at three locations: i) an air intake point for the tunnel system, ii) the air exhaust point for the upper tunnel, and iii) the air exhaust point for the lower tunnel. At each location, two consecutive 24 h samples were collected in the fall of 2017 by pumping air through the carbon traps at a constant pumping rate of 1.06 L/min. A mass flow controller was used to maintain a constant air pumping rate.

The carbon trap samples were analyzed by E-Flux to measure the mass of  $CO_2$  on each trap. <sup>14</sup>C measurements were used to apportion the mass of  $CO_2$  in each sample between modern sources and fossil fuel sources (Hua et al., 2013; McCoy et al., 2015). For the aboveground traps, the mass of fossil fuel-associated  $CO_2$  was converted into a carbon flux by E-Flux (E-Flux, 2014). For the tunnel carbon trap cartridges, the  $CO_2$  mass was converted into a concentration in tunnel air using the known sample volume. This concentration was converted into a flux by multiplying the concentration by the forced air ventilation rate for the tunnel. The  $CO_2$  flux rate was used to calculate a fuel degradation rate using the stoichiometry of fuel degradation: 1 mol  $C_{11}H_{24}$  yields 11 mol  $CO_2$ .

#### 2.2. Temperature measurements

Vertical temperature profiles were collected October 2017 and April 2019. During both events, temperature profiles were measured at the four monitoring wells accessed from the lower access tunnel. One outside well was measured in October 2017 and seven outside wells

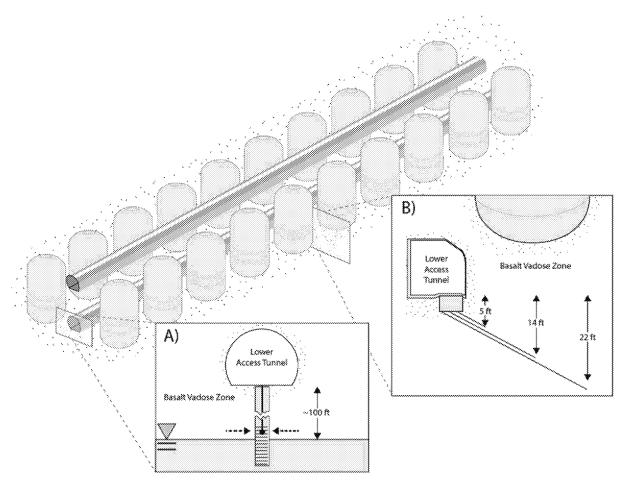


Fig. 1. Design of soil gas sample points accessible from Lower Access Tunnel. (A) Monitoring wells screened partly above the water table. (B) Soil gas monitoring points installed below each active tank. Distances shown are depths below the floor of the lower tunnel.

were measured in April 2019. Temperature measurements were obtained using a high accuracy Type-T thermocouple (Physitemp Instruments). During the October 2017 event, well air temperatures were measured two ways: 1) by allowing the thermocouple to hang vertically at each measurement depth in air within the well; and 2) by pressing the thermocouple against the sidewall using a pipe test-ball

plug to obtain well sidewall temperatures. At each depth, the thermocouple reading typically stabilized within 2–3 min. The two temperature measurement techniques provided similar results. In April 2019, only well air temperatures (method 1) were measured because the two measurement methods yielded comparable results in October 2017. In October 2017, temperature measurements were collected at five-foot

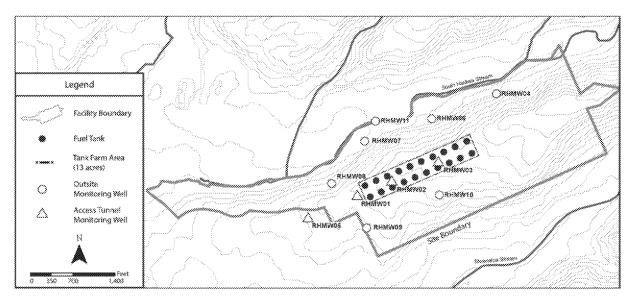


Fig. 2. Monitoring well locations used for this study.

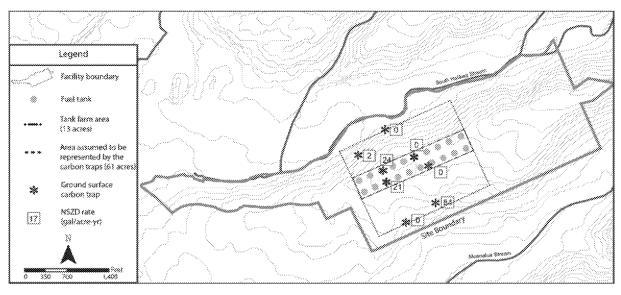


Fig. 3. Ground surface carbon trap locations and results.

(1.5 m) depth intervals from the ground surface to the bottom of each well. In April 2019, variable depth intervals were used ranging from 1 ft. to 20 ft. (0.3 to 6 m).

#### 2.3. Methane, oxygen, CO2, and differential pressure

Methane, oxygen, CO2, and differential pressure were measured in September 2017 at the soil gas monitoring points underlying the Facility tanks and at in-tunnel monitoring wells with screens partially above the water table (i.e., RHMW02, RHMW03, and RHMW05). The monitoring wells were sealed with a gas-tight cap at least 24 h before sample collection. At each sample point, a syringe pump was used to pump 750 mL of headspace vapor into a Tedlar bag. For these monitoring locations, the sample was collected using a weighted 1/8 in. (3 mm) nylon tube threaded through the gas-tight cap and lowered into the well to a depth of two feet above the water table so that the sample was collected within the uncased well interval, immediately above the water table. A GEM5000 Landfill Gas Meter was used to measure oxygen, CO2, and methane concentrations in the bag. The meter reading typically stabilized after approximately 1 min (i.e., 500 mL based on a pumping rate for the landfill gas meter of approximately 500 mL/min), and the reading was recorded when the bag was almost emptied by the meter. A charcoal filter cartridge was installed in the sample line between the water filter and the Tedlar bag to prevent false positive methane readings associated with petroleum vapors in the samples. The charcoal filter removes larger petroleum VOCs, but does not remove methane (Jewell and Wilson, 2011). Following completion of the fixed gas readings, differential pressure was measured by connecting the GEM5000 directly to the soil vapor well or monitoring well.

For all of the monitoring well headspace sample locations and 18 of the below-tank soil gas points, samples were also collected using a  $2.7\,L$  Summa canister for analysis of oxygen,  $CO_2$ , methane, and nitrogen by EPA Method 3C by Alpha Analytical Laboratory, Westborough, MA. Samples were analyzed for an expanded list of 90 petroleum VOCs by EPA Method TO-15. Total petroleum VOC concentrations were low (6 to 300 ppbv; median = 20 ppb) in all samples and are not discussed further.

#### 3. Results

#### 3.1. Methane, oxygen, CO2

High oxygen and low CO2 concentrations were recorded at almost

all measurement locations. In the 47 below-tank soil vapor points, oxygen concentrations ranged from 13.7% to 20.6%, with only two readings below 18%.  $CO_2$  concentrations ranged from 0.1% to 3.2%, with most readings less than 1%. For the well headspace samples, oxygen was 6.6–21% and  $CO_2$  was 0.1–8.5%. Methane was never detected in any measurement location using either the landfill gas meter (detection limit = 0.1%) or samples analyzed off-site by EPA Method 3C (detection limit = 0.06%). These results show an aerobic environment throughout the vadose zone. The lowest oxygen concentrations were measured in the headspaces of RHMW02 (6.6%) and RHMW03 (17%), locations where the temperature measurements indicated the occurrence of NSZD. The results for the individual sample points are provided as supplemental materials, Table S.1.

#### 3.2. Differential pressure

For 39 of the 46 below-tank soil vapor wells tested and three of four monitoring wells, the differential pressure measurements showed a negative pressure in the tunnel relative to the basalt (i.e., a pressure gradient indicating gas flow from the vadose zone into the tunnel). At most of these locations, the differential pressure was greater than 0.1 in.  $\rm H_2O$  (i.e., > 25 Pa). For comparison, a differential pressure of 0.02 in.  $\rm H_2O$  (5 Pa) is typically considered sufficient to support advective flow for vapor intrusion mitigation (i.e., sufficient for effective sub-slab depressurization systems). These results indicate that tunnel exhaust system maintains a negative air pressure that supports advective air flow from the vadose zone into the tunnels, mimicking the effects of a soil vapor extraction system.

#### 3.3. Carbon trap results

Eight passive  $\mathrm{CO}_2$  traps were used to measure the flux of fossil fuel-associated  $\mathrm{CO}_2$  to the ground surface. No fossil fuel  $\mathrm{CO}_2$  was detected on four of the traps ( < 0.001 g). For the remaining four traps, over the 14-day deployment time, the mass of fossil fuel  $\mathrm{CO}_2$  accumulated on each trap ranged from 0.002 g to 0.06 g, corresponding to equivalent NSZD rates of 2 to 84 gal/acre/yr (19 to 784 kg/ha/yr) (Fig. 3). The average NSZD rate across the eight traps was 16 +/-29 gal/acre-yr (149 +/-271 kg/ha/yr). The variability in NSZD rates between traps was not unexpected due to i) the large vertical distance of greater than 300 ft. between the likely NSZD reaction zone and ground surface, and ii) the heterogenous spatial nature of  $\mathrm{CO}_2$  flux to the surface that can cause orders of magnitude differences in spatial samples (e.g., Garg

Table 1
Tunnel system carbon cartridge results.

Sample	Fossil fuel CO <sub>2</sub> (g)
Lower tunnel air exhaust day 1	0.081
Lower tunnel air exhaust day 2	0.085
Upper tunnel air exhaust day 1	0.022
Upper tunnel air exhaust day 2	0.037
Tunnel air intake day 1	0.033
Tunnel air intake day 2	-0.006

et al., 2017). A layer of variable thickness lower-permeability saprolite at ground surface directly above the tanks and exposed basalt layers north and south of the tanks may affect the area where  $\mathrm{CO}_2$  from NSZD is expressed at ground surface. An estimate of overall NSZD attributable to the flux of  $\mathrm{CO}_2$  to ground surface was calculated by multiplying the average NSZD rate from the eight traps (16 gal/acre-yr) by the ground surface area at the facility within the carbon trap deployment area (61 acres) yielding a site-wide NSZD rate of 980 gal/year. Note that the 61 acre ground surface area includes the approximately 13 acre area of the tank farm plus additional land area to the north and south included within the carbon trap test area to evaluate lateral migration of  $\mathrm{CO}_2$  within the subsurface (Fig. 3).

In the second carbon trap method, six carbon cartridges were used to trap  $CO_2$  from a known volume of air (1401 L to 1540 L) from the tunnel system that provides access to the fuel storage tanks. Following a 24 h sample period, the mass of fossil fuel  $CO_2$  accumulated on each trap ranged from -0.006 g to +0.085 g (Table 1). The small negative value for one of the samples at the tunnel air intake point reflects analytical variability and uncertainly associated with use of  $^{14}C$  composition to distinguish between modern  $CO_2$  and fossil fuel  $CO_2$ .

The detection of excess fossil fuel  $\mathrm{CO}_2$  at tunnel air intake was not expected because the  $^{14}\mathrm{C}$  correction accounts for the typical composition of  $\mathrm{CO}_2$  in atmospheric air (E-Flux, 2014). However, during sample collection, a large diesel generator was operating outdoors approximately 50 ft. from the air intake where the intake air sample was collected. The generator may have been a source of the excess fossil fuel  $\mathrm{CO}_2$  in the intake air sample collected on Day 1 (Table 1). For safety reasons, no combustion engines or other fossil fuel combustion sources are allowed within the tunnel system. As a result, the increase in fossil fuel  $\mathrm{CO}_2$  between the tunnel air intake and the tunnel air exhaust points indicates capture of  $\mathrm{CO}_2$  from the biodegradation of LNAPL sources areas within the basalt.

The tunnel system has two primary air intakes; the second air intake is located several hundred feet from any combustion sources. Because testing was conducted at only one of the air intake points, there was some uncertainty regarding the average concentration of excess fossil fuel  $\mathrm{CO}_2$  in the air being taken into the tunnel system during the testing program. To address this uncertainty, upper and lower bound NSZD rates were calculated for NSZD attributable to fossil fuel  $\mathrm{CO}_2$  at the tunnel air exhaust points. The upper bound NSZD rates were calculated assuming that 100% of the fossil fuel  $\mathrm{CO}_2$  at the tunnel exhaust points was attributable to biodegradation of LNAPL. The lower bound NSZD rates were calculated based on the difference in fossil fuel  $\mathrm{CO}_2$  between the measured tunnel air intake and the tunnel air exhaust.

Combining the NSZD attributable to the flux of fossil fuel  $\rm CO_2$  to the ground surface with the NSZD attributable to the flux of fossil fuel  $\rm CO_2$  into the access tunnel system yields an overall NSZD rate at the facility of 4600 to 7400 gal/year (17,000 to 28,000 L/yr; Table 2). Assuming a tank farm area of 13 acres, this corresponds to a NSZD rate of 350 to 570 gal per acre per year (3200 to 5300 kg/ha/yr). Note that an area of 61 acres was used to calculate the  $\rm CO_2$  flux at ground surface, corresponding to the surface area covered by the network of ground surface carbon traps. However, a smaller area of 13 acres was used to estimate the overall NSZD rate per unit area. 13 acres corresponds to the area containing the 20 fuel tanks (Fig. 3). This is the maximum area

Table 2
NSZD rates attributable to flux of fossil fuel CO<sub>2</sub>.

Flux pathway	Lower bound rate (Gallons/Year)	Upper bound rate (Gallons/Year)
Upper tunnel exhaust	200	530
Lower tunnel exhaust	3400	5900
Ground surface (Best Estimate)		980
TOTAL SITEWIDE NSZD RATE	4600	7400

impacted by fuel releases from the facility assuming that lateral migration of LNAPL has been minimal. The assumed LNAPL-impacted area affects NSZD rate per unit area but does not affect the total NSZD rate for the facility estimated from the flux of fossil fuel  ${\rm CO}_2$ .

#### 3.4. Temperature results

Most applications of the temperature method for quantifying NSZD rates have utilized in-place thermocouples to record daily vertical temperature profiles over a period of months or longer in the vadose zone at locations within and outside the petroleum impacted area (Warren and Bekins, 2015; Askarani et al., 2018). Long-term installation of temperature profiling equipment was determined not to be feasible at this facility. However, Sweeney and Riric (2014) indicate that "snap shot" temperature profiles provide a reliable way to understand in-situ biodegradation. At this site, the thick vadose zone (≅120 ft. from the base of the fuel tanks to the water table) was expected to yield a more stable vertical temperature profile compared to sites with shallow groundwater, increasing the reliability of the snap shot approach.

Subsurface temperatures were measured during two field events: October 2017 and April 2019 (supplemental materials Table S.2 and S.3). The first event included four monitoring wells installed inside the lower access tunnel and one well installed outside the tunnel system. The second field program included these five wells plus six additional wells installed outside the tunnel system. For each well, temperatures were measured at 16 to 61 depth intervals from the surface to the bottom of the well, generally 10 ft. to 20 ft. (3 to 6 m) below the water table. During the October 2017 event, measurements of well air temperature and well wall temperature yielded similar results (Fig. 4). Based on this finding, only well air temperatures were measured during the April 2019 event. For consistency between the two events, the well air temperature data have been used for the evaluation of NSZD rates.

The seven monitoring wells (used in this study) outside of the lower access tunnel are located north or south of the tank farm area (Fig. 2). These wells exhibited relatively consistent vertical temperature profiles with temperatures near ground surface that were close to the mean annual air temperature at the Honolulu International Airport 25.4 °C (1981–2010; National Oceanic and Atmospheric Administration (NOAA), 2020). For these wells, temperature decreased with depth down to the groundwater reaching a temperature of 21.0 °C to 22.5 °C, consistent with background groundwater temperatures in the area (supplemental materials Table S.3). None of these wells exhibited an increase in temperature within the depth interval between the base of the fuel tanks and the water table, suggesting an absence of subsurface heating associated with biodegradation of LNAPL.

The four wells located inside the lower access tunnel showed very consistent temperature profiles between the October 2017 and April 2019 field events particularly at depths of more than 15 ft. below the top of the well. Although the lower tunnel is located more than 350 ft. (110 m) below ground surface, the use of ambient air for tunnel ventilation is expected to cause some seasonal variation in tunnel temperature that could impact vadose zone temperatures within a few feet of the tunnel.

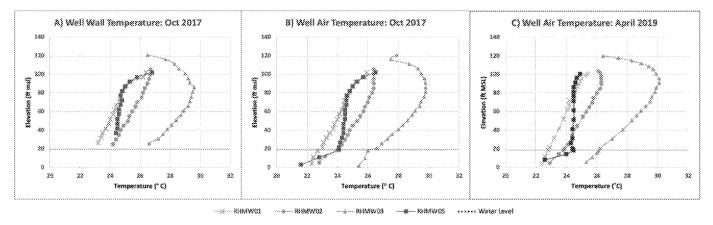


Fig. 4. Vertical temperature profiles for tunnel monitoring wells.

For the purpose of determining NSZD rates, vertical temperature profiles are used to determine the upward temperature gradient (from heat source to the lower tunnel) and downward temperature gradients (from heat source to groundwater) from the aerobic NSZD reaction zone between the lower tunnel and groundwater. These temperature gradients were used to determine temperature-based NSZD rates as described in Sweeney and Ririe (2014), Warren and Bekins (2015), and Sale et al., 2014; Sale et al., 2018b. Determining the upward temperature gradient attributable to subsurface heating typically requires a background location to correct for the effect of seasonal temperature variations on shallow vadose zone temperatures (Askarani et al., 2018).

Two tunnel wells located within the tank farm (RHMW02 and RHWM03) exhibited temperatures profiles consistent with a subsurface heat source below the lower tunnel within the depth interval of 80 ft. to 100 ft. (24 to 30 m) above mean sea level (msl). Because all the site soil gas and high-permeability geology indicates that NSZD-related biodegradation at this site is aerobic, the temperature profiles provide reliable information about the vertical interval of LNAPL in the vadose zone in the vicinity of the monitoring wells. At these two locations, the groundwater temperature at the top of the water table (23.8 °C and 26.0 °C) was well above the background range of 21.0 °C to 22.5 °C, and the groundwater temperature decreased with depth below the water table, two factors consistent with a substantial vadose zone heat source. The other two tunnel wells (RHMW01 and RHMW05) are located between the tank farm area and a large pumping well that likely controls the flow of groundwater within the area. Assuming groundwater flow from the tank farm to the pumping well, RHMW01 is located at the downgradient edge of the tank farm and RHMW05 is located approximately halfway between the edge of the tank farm and the pumping well. These two wells exhibited elevated groundwater temperatures at the top of the water table (22.8 °C and 24.5 °C), but vadose zone temperature profiles were less indicative of vadose zone heating, suggesting that these two wells are both located downgradient of the primary NSZD heat generation area. While the temperature profile for RHMW05 shows no evidence of vadose zone heating, the temperature profile for RHMW01 show a small inflection at depth of approximately 25 ft. below the lower tunnel floor that could be indicative of a small amount of heat generation (see Supplemental Materials).

Because the temperature profile for RHMW01 was potentially consistent with either background temperature conditions or with a small amount of vadose zone heat generation, two set of NSZD rates were calculated: i) NSZD rates were calculated for three locations (RHMW01, RHMW02, and RHMW03) using RHMW05 for background correction and ii) NSZD rates were calculated for two locations (RHMW02, and RHMW03) using RHMW01 for background correction. The NSZD calculations are provided as supplemental materials and the results are summarized in Table 3.

Averaging across the three wells located within the tank farm area

Table 3

NSZD Rates from Temperature Profiles in Monitoring Wells Extending from Lower Access Tunnel to Groundwater.

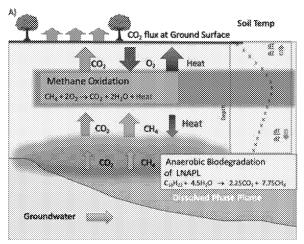
	RHWM01	RHMW02	RHMW03
Upward Heat Flux (W/m²)	0-0.07	0.52-0.67	1.59-1.92
Downward Heat Flux (W/m <sup>2</sup> )	0-0.15	0.02 - 0.17	0.10-0.31
NSZD Rate (gal/acre-year)	0-200	490–750	1500-2000
TOTAL SITEWIDE NSZD RATE (gallons per year)	8600 to 13,0	000	

and using a tank farm area of 13 acres, the temperature data indicate an overall NSZD rate for the facility of 8600 gal/year to 13,000 gal/year (33,000 to 49,000 L/yr), within a factor of two of the rate range estimated based on the  $\rm CO_2$  flux.

#### 4. Discussion

Two different methods (CO2 flux and heat flux) were used to measure the rate of NSZD at a large petroleum storage facility in Hawaii. Both fossil fuel-associated CO2 and excess heat were measured at the facility providing strong evidence that NSZD is occurring. The estimated petroleum degradation rates were 4600 to 7400 gal/year (17,000 to 28,000 L/yr) based on CO<sub>2</sub> flux and 8600 to 13,000 gal/year (33,000 to 49,000 L/yr) based on heat flux. The relatively close agreement in NSZD rates between the two methods provides increased confidence in the overall findings. In addition, the monitoring wells adjacent to the tanks and screened below likely zones of LNAPL within the vadose zone showed groundwater temperatures were elevated by 3 °C to 5 °C relative to monitoring wells not located in the immediate vicinity of the tanks (data not shown), confirming the presence of a large biodegradation-related heat source in the vadose zone. Note that the datasets for the two evaluation methods (CO<sub>2</sub> flux and heat flux) do not support an evaluation of spatial consistency (i.e., whether or not the two methods indicate that NSZD is occurring in the same area).

Oxygen,  $\mathrm{CO}_2$ , and methane concentrations were measured in vadose zone samples collected from available soil gas monitoring points installed below the fuel tanks and well headspace samples for monitoring wells screened across the water table. These samples showed no detectable methane ( < 0.1%) in any samples and oxygen concentrations indicative of aerobic conditions throughout the vadose zone. These results indicate that the common NSZD two-step process of anaerobic methanogenic degradation of petroleum constituents within the LNAPL source area and methane oxidation at a shallower depth interval in the vadose zone (e.g., Garg et al., 2017; Warren and Bekins, 2015) is not applicable at this site. Instead, the occurrence of high oxygen concentrations throughout the vadose zone suggest that NSZD is occurring



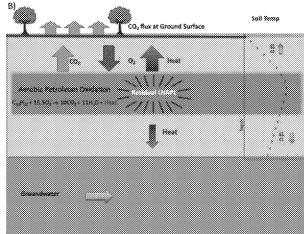


Fig. 5. Conceptual model of A) conventional two-stage NSZD in unconsolidated media and B) NSZD through direct aerobic biodegradation of LNAPL in high permeability media such as basalt. The available soil gas and geologic data support an aerobic NSZD Conceptual Site Model at the Red Hill Facility. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

through the direct aerobic degradation of LNAPL within the vadose zone (§§. §) and that the elevated temperature in the vertical temperature profiles at two of the monitoring wells correspond to the location of LNAPL that is being biodegraded aerobically.

Although no methane was detected above or below the LNAPL source, no methane or oxygen measurements were taken directly within the LNAPL source area. Thus, it is possible that the LNAPL source area may contain an anaerobic methanogenic core with methane oxidation occurring above and below this anaerobic core.

The differential pressure measurements indicate that the pressure within the lower tunnel is lower than the pressure in the surrounding basalt, supporting the flow of air from the basalt into the tunnel. In addition, the measurement of fossil fuel-associated CO<sub>2</sub> in the lower tunnel is consistent with air flow from the LNAPL source area into the lower tunnel. Together, these results indicate that the low pressure in the lower tunnel is acting as a very large vapor extraction system inducing air flow through the vadose zone into the lower tunnel. This induced air flow may contribute to the maintenance of aerobic conditions within the LNAPL source area. To our knowledge, this is the first petroleum release site where the available data support a conceptual model of direct aerobic biodegradation of LNAPL in the vadose zone and provides NSZD rates of LNAPL in a basalt vadose zone.

#### **Declaration of Competing Interest**

None.

#### Acknowledgements

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jconhyd.2020.103729.

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# ATTACHMENT 2

Boring Logs for RHMW01 (formerly called B-V1D), RHMW02 and RHMW03 In-Tunnel Wells

					I Bulk Storage F	acili	ty	Boring/Monitoring Well No. Project No. CTO 0229	B-V1D
ł					sal Aquifer		genennenheitetta	ELEVATION: 102.56	
ł	DRILLE				Associates, Inc.				ance Williams
F	PRILL P	राG:			EH5, Portable C	ore D	rill	DEPTH TO WATER> FIRST: 86.0	COMPL.: 86.1
	ORING	3 AN						AMETER (inch): 1"	
	Correct Elevation Boring Length	In the control of the		Graphic Log	SOIL DESCRIPTION	WELL CONSTRUCTION			
rtains only to this boring and she not be interpreted as being indicitive of the site.		- 10 10 20 30 40	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16	NM 172 NM NM 99.2 NM NM 124 NM	SS.	100 83 71 0 33 100 105 93 96 100 100 100 100 100 98	Grap.	Concrete 0-2' over fine to coarse sand with fine grave and silt 2-2.5; basalt 2.5'; no odor Small to large vesicles; no odor; 10YR 3/1 Small to medium vesicles; no odor; 10YR 3/1 to 2/1 Small vesicles; no odor; 5YR 3/2 to 10YR 2/2 Small to medium vesicles; no odor; 5YR 3/2 to 10YR 2/2 Small to large vesicles; no odor; 10YR 2/2 Small to large vesicles; no odor; 10YR 2/2 to 3/2 Primarily small to medium vesicles; no odor; 10YR 2/2 Small to primarily large vesicles; no odor; 10YR 2/2 5YR 3/2 to 10YR 3/1 Small to large vesicles; no odor; 10YR 3/1 to 5YR 3/2 Small to medium vesicles; no odor; 5YR 3/2 to 10YR 3/1 Small to large vesicles; no odor; 5YR 3/2 to 10YR 3/1 Small to large vesicles; no odor; 5YR 3/2 to 10YR 3/1 Small to large vesicles; no odor; 10YR 2/2 to 5YR 3/2 Void Small to medium vesicles; no odor; 10YR 2/2 to 5YR 3/2 Void Small to medium vesicles; no odor; 10YR 2/2 to 5YR 3/2 Void Small to medium vesicles; no odor; 10YR 2/2 to 5YR 3/2 Void Small to medium vesicles; no odor; 10YR 2/2 to 5YR 3/2 Void	/el
tion pe	43.36	-	17	1.0		89		Small to medium vesicles; no odor; 10YR 2/2 to 5YF 3/2	
This information pertains		- 60	18	6.9		100		Small to large vesicles; no odor; 10YR 3/1 to 2/2 to 5YR 3/2	
This	<b>3</b> 8.36	-	19	1.8		83		Small to large vesicles; no odor; 10YR 2/5 to 5YR 3.	/2
	34.26	70	20	0.0		92		Small to medium vesicles; no odor; 10YR 2/1 to 2/2 5YR 3/2	tp C
	29.16		21	0.0	RH-BR-V1D-S01	102		Small vesicles; no odor; 10YR 2/1	
	Corr	ectec	l elev	/ations	are provided for	angle	bori	ngs.	Appendix 1 Page1 of 2

gramma gramma

					II Bulk Storage F	Facili	ty		oring Well No.	B-V1D
I	OCAT	ON:	V1	D - Ba	sal Aquifer			ELEVATION: 102.56		
L	RILLE				Associates, Inc.			DATE DRILLED: 2/13/01		nce Williams
. 4-	PRILL F	RIG:	SAI	<u>TECH</u>	EH5, Portable C	ore D	<u>)rill</u>	DEPTH TO WATER>	FIRST: 86.0	COMPL.: 86.1
-	ORING	3 AN	GLE	: 90		<b></b>		AMETER (inch): 1"		
	Correct Elevation Boring Length	ed on/ I (ft)	Core Run Number	PID Reading (ppm)	Sample Number	Core Recovery %	Graphic Log	SOIL DESCRIPT	ION	WELL CONSTRUCTION
	24.06	- 80 -	22	0		100		Medium vesicles; no odor; 10YR	2/2	
	18.86	-	23	0.0	RH-BR-V1D-S02	106		Medium vesicles; no odor; 10YR	2/2	
- Constitution of the Cons	15.66	-	24	0.0		96		Large vesicles; no odor; 10YR 2/	1	
	10.16 9.56	90 - -	25	0.0		86		Small vesicles; no odor; 10YR 2/	2	
	6.56 4.96 4.96 2.56	- - 100	26 27	0.0 0.0	RH-BR-V1D-S03	56 50		Medium vesicles; clinker zone; no Medium vesicles; clinker zone; no Clinker zone  B-V1D terminated at 100.0'	o odor; 10YR 2/1 o odor; 10YR 2/2	
to this boring and sr not be interpreted		- - - - - - - - - 120								
		130								
***************************************		- 140								
		- 150 -								
	Corr	ected	l ele	vations	s are provided for	angl	e bor	ings.		Appendix 1 Page2 of 2

, compared to the Compared Com

Station Name: RHMW02 Location: **RHSF** Location Type: Monitoring Well Location Description: lower access tunnel, N of Tank 6 Establishing Company: TEC Inc. Drilling Foreman: Dean McLure Drilling Company: Valley Well Drilling Geologist: N. Griffin/S. MacMillan Ground Surface Elevation (ft): 106.57 Datum: MSL Drilling Sampling Method: **Rock Coring** Borehole Diameter (in): 5 Total Depth (ft): 103.5 Date Drilling Started: 27 July 2005 Date Drilling Ended: 28 July 2005 Remarks: Well Construction Well Fill USCS Sail Description Soil Sample CON Concrete - gray. Cement FILL Sand base Grout Œ Basalt boulders. CON Concrete - Rate = 5/10.5. Basalt - brownish black (5YR 2/1), RQD = 68.3%, 60% vesicles: 3mm - 7mm. 100% recovery, no odor, PID sample head space: 0 ppm. Basalt - brownish black (5YR 2/1), Rate = 1/4, RQD = 69.4%, 40% vesicles: 5mm 1 cm, 69% recovery, no odor, PID sample head space; 0 ppm. Basalt - brownish black (5YR 2/1), Rate = 5/15, RQD = 100%, 10% vesicles: 0.5cm - 1cm, 100% recovery. Basalt - brownish black (5YR 2/1), Rate = 5/10, RQD = 86.7%, 10% vesicles: 2mm - 4mm, 100% recovery, no odor. PID sample head space: 0 ppm. Basalt - brownish black (5YR 2/1), Rate = 5/5, RQD = 80.8%, 80% vesicles: 1mm - 2mm, 100% recovery. Basalt - brownish black (5YR 2/1). Rate = 5/5, RQD = 80.6%, 60% vesicles: 5mm, 100% recovery, verticle fractures present - possible shearing from drill. Basalt - brownish black (5YR 2/1), RQD = 43.3%, 75% vesicles: 3mm - 5mm, 100% recovery. Basalt - red, RQD = 43.3%, 80% vesicles: 2mm, 100% recovery. ΙE Basalt - dusky brown (5YR 2/2), Rate = 5/5, RQD = 46.7%, 60% vesicles, 2mm -3mm, 100% recovery, no odor.

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Station Name: RHMW02 Location: **RHSF** Location Type: Monitoring Well Location Description: lower access tunnel, N of Tank 6 Establishing Company: TEC Inc. Drilling Foreman: Dean McLure Drilling Company: Valley Well Drilling Ground Surface Elevation (ft): 106.57 Datum: MSL Geologist: N. Griffin/S. MacMillan **Drilling Sampling Method:** Borehole Diameter (in): 5 Rock Coring Total Depth (ft): 103.5 Date Drilling Started: 27 July 2005 Date Drilling Ended: 28 July 2005 Remarks: Basalt - grayish black (N2), Rate = 5/5, RQD = 81.7%, 40% vesicles: 3mm - 5mm. 33 100% recovery, no odor, PID sample head space: 0 ppm. Basalt - grayish black (N2), Rate = 5/5, RQD = 81.7%, 40% vesicles: 3mm - 5mm, 100% recovery, no odor, PID sample head space: 0 ppm. Bentonite Basalt - gravish black (N2), Rate = 8/5, RQD = 66.7%, 60% vesicles; 4mm - 10mm, 40 100% recovery, no odor. Basalt - grayish black to moderate brown (N2 to 5YR 4/4), Rate = 8/5, RQD = 66.7%, 70% vesicles: 1mm - 4mm, 100% recovery, no odor. Basalt - grayish black (N2). Rate = 8/5, RQD = 66.7%, 60% vesicles, 100% recovery, no odor Basalt - greyish black (N2), Rate = 8/5, RQD = 43,3%, 70% vesicles; 2mm - 4mm, 45 90% recovery Basalt - gravish black (N2), Rate = 8/5, RQD = 43.3%, 50% vesicles: 5mm - 10mm. 90% recovery Basalt - grayish black (N2), Rate = 8/5, RQD = 43.3%, 50-70% vesicles: 4mm -10mm, 90% recovery. NSNA 0% recovery. 50 Basalt - moderate brown to dusky yellowish brown (5YR 4/4 to 10YR 2/2), Rate = 5/10, RQD = 0%, 70-80% vesicles: 2mm - 3mm, 20% recovery, no odor, PID sample head space: 0 ppm, soft drilling. 55 Basalt - grayish black to blackish red (N2 to 5R 2/2), Rate = 5/10, RQD = 0%. 10% vesicles: 1mm - 5mm, 25% recovery, PID sample head space: 0.4 ppm. clinker zone. 60Basalt - grayish black to blackish red (N2 to 5R 2/2), Rate = 5/10, RQD = 0% 25% vesicles: 1mm - 5mm, 25% recovery, PID sample head space: 0 ppm, clinker zone. Pellets Basalt - grayish black to blackish red (N2 to 5R 2/2), Rate = 8/5, RQD = 40%. 1mm - 5mm, 90% recovery. 65Basalt - dark gray (N3). Rate = 8/5, RQD = 40%, 1 mm, 90% recovery, PiD sample head space: 0 ppm, blue rock,

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	1 0	tion Name - PRIBATES			203 55	
Location: RHSF		tion Name: <b>RHMW02</b>		ype: Monitoring	Well	
Location Description: lov		unnel, N of Tank 6		mpany: <b>TEC Inc.</b>		
Drilling Foreman: <b>Dean</b> I	McLure		Drilling Compan	y: Valley Well Dri	lling	
Geologist: N. Griffin/S	. MacMillan	Ground Surface Elev	vation (ft): 106.5	57	Datum: MS	L
Drilling Sampling Method:	Rock Cor	ing	Bore	ehole Diameter (in):	5	
Total Depth (ft): 103.5	Date Drilling	Started: 27 July 20	005	Date Drilling Ended:	28 July 200	5
Remarks:						
70 - Sand  80 - Sand  90 - Sand	Œ	Basalt - moderate brown  Basalt - medium gray (N  3mm, 100% recovery, c  Basalt - dark gray (N4),  75% recovery, blue rock  Basalt - moderate brown possible weak zone,  Basalt - moderate brown  RQD = 96.7%,  Basalt - moderate brown  RQD = 96.7%,  Basalt - dark gray (N3),  100% recovery, no odo  Basalt - dark gray (N2),  100% recovery, no odo  Basalt - dark gray (N2),  100% recovery, no odo  Basalt - dark gray (N3),  100% recovery, no odo  Basalt - dark gray (N3),  100% recovery, no odo  Basalt - dark gray (N3),  100% recovery, no odo  Basalt - dark gray (N3),  100% recovery, no odo  Basalt - dark gray (N3),  100% recovery, no odo  Basalt - dark gray (N3),  100% recovery, no odo  Basalt - dark gray to gravesicles: 1mm - 5mm, 9  Basalt - dark gray to gravesicles: 5mm - 10mm,  Basalt - dark gray to gravesicles: 1mm - 5mm, 9  Basalt - dark gray to gravesicles: 1mm - 5mm, 9  Basalt - dark gray to gravesicles: 2mm - 5mm, 9  Basalt - grayish brown to 50% vesicles: 2 mm - 5	is), Rate = 5/10, RG core barrel and rods:  Rate = 15/3, RQD k.  atural horizontal frac in (5YR 3/4), Rate = in to grayish brown (i)  QD = 96.7%, 80% v is to vesicular basal N2), Rate = 15/5, RQD r, PID sample head in (5YR 3/4), Rate = very, no odor, PID s Rate = 15/5, RQD r, PID sample head in (5YR 3/4), Rate = very, no odor, PID s Rate = 15/5, RQD r, PID sample head in (5YR 3/4), Rate = no odor, PID sample head in (5YR 3/4), Rate = no odor, PID sample head in (5YR 3/4), Rate = no odor, PID sample head in (5YR 3/4), Rate = no odor, PID sample head in to light brown (5YR inm - 3mm, 100% rec ayish black (N3 to N 8% recovery, no od ayish black (N3 to N 98% recovery, no od ayish black (N3 to N 98% recovery, no od ayish black (N3 to N 98% recovery, no od odark gray (5YR 3/	QD = 63.3% 10-20% vistuck.  = 16.7% <10% vesicle clures, approx. 0.5 - 1"  = 15/3, RQD = 16.7% s  5YR 3/4 to 5YR 3/2).  resicles. 1st 3 clinker 0 lt.  rQD = 96.7%, 2 clinker  = 63.3%, 80% vesicles space: 2 ppm.  = 15/5, RQD = 63.3% s  sample head space: 2 lt = 63.3%, 80% vesicles space: 2 ppm.  = 65%, 90% vesicles space: 2 ppm.  = 65%, 90% vesicles: 1 space: 0 ppm.  = 65%, 85% vesicles: 1 space: 0 ppm.  = 15/5, RQD = 65%, 85 le head space: 0 ppm.  = 65%, 85% vesicles: 1 space: 0 ppm.  = 15/5, RQD = 65%, 85 le head space: 0 ppm.  = 15/5, RQD = 65%, 85 le head space: 0 ppm.  = 15/5, RQD = 65%, 85% vesicles: 1 space: 0 ppm.  = 15/5, RQD = 65%, 85% vesicles: 1 space: 0 ppm.  = 15/5, RQD = 65%, 85% vesicles: 1 space: 0 ppm.  = 15/5, RQD = 65%, 85% vesicles: 1 space: 0 ppm.  = 15/5, RQD = 65%, 85% vesicles: 1 space: 0 ppm.  = 15/5, RQD = 65%, 85% vesicles: 1 space: 0 ppm.  = 15/5, RQD = 65%, 85% vesicles: 1 space: 0 ppm.  = 15/5, RQD = 65%, 85% vesicles: 1 space: 0 ppm.  = 15/5, RQD = 65%, 85% vesicles: 1 space: 0 ppm.  = 15/5, RQD = 65%, 85% vesicles: 1 space: 0 ppm.  = 15/5, RQD = 65%, 85% vesicles: 1 space: 0 ppm.	esicles: 1mm- es: 4mm - 1mm. thick. weathered,  S diameter at 83'2, cream : 1mm - 5mm.  1mm - 5mm.  timm - 4mm.  ***wesicles: 1mm timm - 5mm.  te = 15/5, RQD ample head = 60%, 80% pace: 0 ppm. = 60%, 85% space: 0 ppm. = 60%, 85% space: 0 ppm. = 60%, 80% pace: 0 ppm. = 60%, 80% pace: 0 ppm. = 80%, 80% pace: 0 ppm.	RHMW02S01

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Location: **RHFSF** Station Name: RHMW03 Location Type: Monitoring Well Location Description: Iower access tunnel, N of Tank 14 Establishing Company: TEC Inc. Drilling Foreman: Tim Robertson Drilling Company: Valley Well Drilling Ground Surface Elevation (ft): 122.11 Datum: MSL Geologist: N. Griffin/S. MacMillan **Drilling Sampling Method:** Borehole Diameter (in): 5 Rock Coring Total Depth (ft): 118 Date Drilling Started: 2 September 2005 Date Drilling Ended: 7 September 2005 Remarks: USCS Well Construction Well Fill Sail Description Soil Sample CON Camant Grout Concrete. Basalt - dark gray to grayish brown (N3 to 5YR 3/2), Rate = 1/30, RQD = 33%. 80% vesicles: 1 mm - 2 mm, 100% recovery, PID sample head space: 0 ppm. Basalt - grayish black (N2), Rate = 3/10, RQD = 73%, 70 - 90% vesicles: 1mm -2mm, 100% recovery, PID sample head space: 0 ppm Basalt - moderate brown (5YR 3/4), Rate = 3/10, RQD = 73%, 70 - 90% vesicles: 1mm - 2mm, 100% recovery. PID sample head space: 0 ppm. Basalt - dark gray (N3), Rate = 3/10, RQD = 73%, 30 - 80% vesicles: 1 mm -10mm, 100% recovery, PID sample head space; 0 ppm. Basalt - dark gray (N3), Rate = 3/10, RQD = 90%, 30 - 80% vesicles: 1 mm -10mm, 100% recovery. PID sample head space; 0 ppm. Basalt - moderate brown (5YR 3/4), Rate = 3/10, RQD = 90%, 70 - 90% vesicles: 1 mm - 5mm, 100% recovery, PID sample head space: 0 ppm. Basalt - light brown (5YR 5/6), Rate = 4.5/12, RQD = 11%, 75 - 95% vesicles: 1 mm - 3mm, 66% recovery, PID sample head space: 0 ppm. Basalt - dark gray (N3), Rate = 4.5/12, RQD = 11%, 80 - 90% vesicles: 1 mm -5mm, 66% recovery. PID sample head space: 0 ppm. Basalt - soft gray. Rate = 1/3. RQD = 42%, highly vessicular, 100% recovery. Basalt - soft gray, Rate = 1/3, RQD = 42%, 100% recovery. Basalt - soft gray, Rate = 1/3, RQD = 42%, highly vessicular, soft - fractured, 100% Basalt - red to soft gray, Rate = 5/18, RQD = 48%, vessicular, 100% recovery. 25 Basalt - red, Rate = 5/18, RQD = 48%, vessicular, soft - fractured, 100% recovery. Bentonite Basalt - red to soft gray, vessicular, fractured, poor recovery, clinker zone. 30

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Location: **RHFSF** Station Name: RHMW03 Location Type: Monitoring Well Location Description: Iower access tunnel, N of Tank 14 Establishing Company: TEC Inc. Drilling Foreman: Tim Robertson Drilling Company: Valley Well Drilling Ground Surface Elevation (ft): 122.11 Datum: MSL Geologist: N. Griffin/S. MacMillan **Drilling Sampling Method: Rock Coring** Borehole Diameter (in): 5 Total Depth (ft): 118 Date Drilling Started: 2 September 2005 Date Drilling Ended: 7 September 2005 Remarks: Basalt - gray to red. Rate = 5/10, RQD = 50%, poor recovery, clinker zone. Basalt - gray to red. Rate = 5/10, RQD = 50%, vessicular, 75% recovery. Basalt - gray to red, Rate = 5/10, RQD = 50%, vessicular, 75% recovery. Basalt - Rate = 5/11, Clinker. Basalt - gray to red, Rate = 5/11, RQD = 60%, very vessicular, 80% recovery. Basalt - gray to red. Rate = 5/10. RQD = 70%, 83% recovery. Basalt - red to gray. Rate = 5/10, RQD = 70%, poor recovery, clinker. ΙE Basalt - red to gray, Rate = 5/10, RQD = 70%, soft, 83% recovery. Basalt - gray, RQD = 50%, glassy, 50% recovery, PID sample head space; 0 ppm. Basalt - no recovery, clinker. Basalt - hard fragmented material, very poor recovery, slow drilling, started in clinker. Basalt - gray, hard, Basalt - hard drilling, rubble zone. Bentonite Basalt - medium dark gray (N4), Rate = 3/63, RQD = 0%, 30 - 50% vesicles: 3 mm - 8 mm, 50% recovery. PID sample head space: 0 ppm. 60 Basalt - grayish black (N2), Rate = 1.5/30, RQD = 0%, 5% vesicles: 2 mm - 3 mm. 100% recovery, no odor, PID sample head space: 0 ppm, mechanically fractured blue stone, rubble at last 2 on top. Basalt - grayish black (N2), Rate = 3/30, RQD = 18%, 5 - 10% vesicles: 2 mm - 3 65 mm, 60% recovery, no odor, PID sample head space; 0 ppm, mechanically fractured blue stone.

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Location: **RHFSF** Station Name: RHMW03 Location Type: Monitoring Well Location Description: Iower access tunnel, N of Tank 14 Establishing Company: TEC Inc. Drilling Foreman: Tim Robertson Drilling Company: Valley Well Drilling Geologist: N. Griffin/S. MacMillan Ground Surface Elevation (ft): 122.11 Datum: MSL **Drilling Sampling Method: Rock Coring** Borehole Diameter (in): 5 Total Depth (ft): 118 Date Drilling Started: 2 September 2005 Date Drilling Ended: 7 September 2005 Remarks: Basalt - grayish black (N2). Rate = 5/30. RQD = 10%, 5 - 10% vesicles: 2 mm - 3 mm, 60% recovery, no odor. PID sample head space: 0 ppm, mechanically 70 fractured blue stone. Basalt - grayish black (N2), Rate = 5/26, AQD = 0%, 5 - 10% vesicles: 1 mm -5mm, 80% recovery, no odor, PID sample head space: 0 ppm, mechanically fractured blue stone. Basalt - grayish black (N2), Rate = 5/26, RQD = 0%, 1% vesicles: 2 mm, 80% recovery, no odor. PID sample head space: 0 ppm, mechanically fractured blue Basalt - dusky yellowish brown (10YR 3/2), Rate = 5/25, RQD = 0%, 30% 80 vesicles: 1 mm, 60% recovery, no odor Basalt - light brown (5YR 5/6), Rate = 5/25, RQD = 0%, 30% vesicles: 1 mm, 60% recovery, no odor. Basalt - grayish black (N2), Rate = 5/25, RQD = 0%, 3 - 5% vesicles: 1 mm - 2 mm. 60% recovery, no odor. 85 Basalt - medium dark gray (N4), Rate = 5/25, RQD = 33%, 60% vesicles: 1 mm, 67% recovery, no odor, Pellets Basalt - grayish black (N2), Rate = 5/19, RQD = 45%, 75% vesicles: 1 mm, 87% Basalt - grayish black (N2), Rate = 5/19, RQD = 45%, 75% vesicles: 1 mm, 87% recovery. Basalt - brownish gray (5YR 4/1), Rate = 5/19, RQD = 45%, 80% vesicles: 1 mm. 87% recovery, highly fractured softer basalt, Basalt - dark gray w/ some light brown clay (N3 w/ 5YR 5/6), Rate = 5/40, RQD = 8.3% 50 - 60% vesicles: 1 mm - 10 mm, 68% recovery, no odor, PID sample head space: 0 ppm. RHMW03S01 sand Basalt - dark gray (N3), Rate = 5/20, RQD = 15%, 40 - 60% vesicles: 1 mm - 10 nm. 35% recovery, poor recovery, possible void - noted quick drop while drilling 100 аррюх. 6.

Page 3 of 4

Location: RHFSF	Station Name: RHMW03	Location	Type: Monitoring	ı Well			
Location Description: lower acce	ss tunnel, N of Tank 14	Establishing C	ompany: <b>TEC Inc.</b>				
Drilling Foreman: Tim Robertso	n	Drilling Compa	any: Valley Well D	rilling			
Geologist: N. Griffin/S. MacMillan Ground Surface Elevation (ft): 122.11 Datum: MS							
Drilling Sampling Method: Rock	Coring	Вс	orehole Diameter (in)	: 5			
Total Depth (ft): 118 Date Dri	illing Started: 2 Septem	ber 2005	Date Drilling Ended	7 September 2005			
Remarks:							
105	85% recovery, no odor.  Basalt - dark gray (N3), med. grained sand piec	Rate = 5/20, no ces.	D = 28%, 40 - 50% vesi I space: 0 ppm. recovery, one small pied D = 0%, 40% vesicles: 1	ce of basalt, some			

# ATTACHMENT 3

Soil Vapor Analytic Results for RHMW01 – RHMW04



# ATTACHMENT B.3.4: SOIL VAPOR AND GROUNDWATER MONITORING WELL HEADSPACE SAMPLE ANALYTICAL RESULTS Red Hill Bulk Fuel Storage Facility, Joint Base Pearl Harbor-Hickam, O'ahu, Hawai'i

		ample ID: ample ID: ate/Time	L1740493-19 2017-10-30 9:12	RHMW02ERH450 L1740493-20 2017-10-26 10:03	RHMW03ERH451 L1740493-21 2017-10-26 11:38	RHMW04ERH452 L1740493-22 2017-10-26 15:03
FIXED GASES BY USEPA METHOD		Matrix:	HEADSPACE	HEADSPACE	HEADSPACE	HEADSPACE
Analyte	7.30	Units	2.000	3.43	2.00	
Carbon Dioxide Methane		%	0,908 <0,051	9.13 <0.057	2.08 <0.058	0,094 J <0.058
Oxygen VOCs BY USEPA METHOD TO-15 (	TARGET ANALYTES)	%	19.9	7.8	18.7	21.8
Analyte Decane (C10)	Class aikane	Units ppbV	<0.25	0,157	3.67	0.628
Dodecane (C12)	alkane	ppbV	<0.5	0.279	1.82	0.755
Heptane	alkane	ppbV	0.51D	0,066	0.851	0.039
n-Hexane	alkane	Vdqq	1.65D	0.132	0.499	0.037
Nonane (C9)	alkane	ppbV	0.18 JD	0.083	3,53	0.089
Octane	alkane	ppbV	0.31D	0.081	2.26	
Pentane	alkane	ppbV	8.69D	8.76	0.869	0.211
Tridecane	alkane	ppbV	<0.5	0.215 J	0.501 J	0.361 J
Undecane	alkane	Vdqq	<0.25	0.247	2.88	0.297
1,3-Butadiene	alkene	Vdqq	<0.1	<0.01	<0.01	<0.01
1-Decene	alkene	Vdqq	<0.25	<0.025	<0.025	<0.025
1-Heptene	alkene	Vdqq	<0.1	<0.01	<0.01	<0.01
1-Hexene	alkene		3.28D	<0.01	<0.01	<0.01
1-Nonene	alkene	₽₽bV	<0.1	<0.01	<0.01	<0.01
1-Octene	alkene	ppbV	<0.1	<0.01	<0.01	<0.01
1-Pentene	alkene	ppbV	6.83D	0.151	0,031	0.019 J
2-Methyl-1-Butene	alkene	Vdqq	0.57D	0.07	0.037	<0.01
cis-2-Pentene	alkene		<0.1	<0.01	<0.01	<0.01
trans-2-Pentene	alkene	ppbV	0.19 JD	0.111	0.035	<0.01
2,2-Dimethylpentane	branched alkane	Vdqq	<0.1	<0.01	<0.01	<0.01
2,3,3-Trimethylpentane	branched alkane	Vdqq	<0.1	0.07	0.084	0.018 J
2,3,4-Trimethylpentane	branched alkane	ppbV	<0.1	0.017 J	0.111	<0.01
2,3-Dimethylbutane	branched alkane	ppbV	0.27D	<0.01	0.138	<0.01
2,3-Dimethylhexane	branched alkane	ppbV	<0.1	<0.01	<0.01	<0.01
2,3-Dimethylpentane	branched alkane	ppbV	<0.1	<0.01	0.205	<0.01
2,4-Dimethylhexane/2,2,3-Trimethylp 2,4-Dimethylpentane		ppbV	<0.25 <0.1	0.036 JB <0.01	0.112 0.104	<0.025 <0.01
2,5-Dimethylhexane	branched alkane	Vdqq Vdqq	<0.1	0.016 J	0.092	<0.01
2-Methylheptane	branched alkane	ppbV	<0.1	<0.01	0.829	<0.01
2-Methylhexane	branched alkane		0.33D	0.044	0.236	0.014 J
2-Methylpentane	branched alkane	ppbV	1.19D	0.754	0.439	0,081 B
3-Ethylhexane	branched alkane	ppbV	<0.1	<0.01	0.099	<0.01
3-Methylheptane	branched alkane	Vdqq	<0.1	0.025	0.52	0.013 J
3-Methylhexane	branched alkane	ppbV	0.52D	0.144	0.515	<0.01
3-Methylpentane	branched alkane	ppbV	0.61D	0.069	0.267	0.022 J
sooctane	branched alkane	ppbV	0.24 JD	0.059	0,189	0.018 J
Isopentane	branched alkane	ppbV	<0.1	<0.01	1,14	<0.01
1-Ethyl-1-Methylcyclopentane	cycloalkane	ppbV	<0.1 16.4D	<0.01 0.175	0.055 0.464	<0.01 0.059
Cyclohexane Cyclopentane	cycloalkane cycloalkane	ppbV ppbV	0.43D	<0.01	0.176	0.295
Methylcyclohexane	cycloalkane	ppbV	0.93D	0.08	1.88	0.025
Methylcyclopentane	cycloalkane	ppbV	0.52D	0.058	0.533	<0.01
1,2,4,5-Tetramethylbenzene	aromatic	ppbV	<0.25	<0.025	0.036 J	<0.025
1,2,4-Trimethylbenzene	aromatic	ppbV	0.31 JD	0.133	2.04	0,133
1,2-Diethylbenzene	aromatic	ppbV	<0.25	<0.025	0.085	<0.025
1,2-Dimethyl-3-Ethylbenzene	aromatic	ppbV	<0.25	<0.025	0.157	<0.025
1,2-Dimethyl-4-Ethylbenzene	aromatic	ppbV	<0.25	<0.025	0.27	<0.025
1,3,5-Trimethylbenzene	aromatic	ppbV	0.11 JD	0,03	0,605	0.032
1,3-Dimethyl-2-Ethylbenzene	aromatic	ppbV	<0.25	<0,025	0,061	<0.025
1,3-Dimethyl-4-Ethylbenzene 1,3-Dimethyl-5-Ethylbenzene	aromatic	Vdqq	<0.25 <0.25	<0.025 <0.025	0.303 0.274	<0.025 <0.025
1,4-Dimethyl-2-Ethylbenzene	aromatic aromatic	ppbV ppbV	<0.25	<0.025	0.236	<0.025
1-Methyl-2-Ethylbenzene	aromatic	ppbV	<0.25	0.026 J	0.679	0.029 J
1-Methyl-2-isopropylbenzene	aromatic	ppbV	0.73D	<0.025	0.032 J	<0.025
1-Methyl-2-N-Propylbenzene	aromatic	Vdqq	<0.25	<0.025	0,316	<0.025
1-Methyl-3-Ethylbenzene	aromatic		<0.25	0.047 J	1.08	0.055
1-Methyl-3-Isopropylbenzene	aromatic	ppbV	<0.25 <0.25	<0.025 <0.025	0.259	<0.025
1-Methyl-3-N-Propylbenzene 1-Methyl-4-Ethylbenzene	aromatic aromatic	ppbV ppbV	<0.1	0.023 J	0.39 0.532	<0.025 0.026
1-Methyl-4-Isopropylbenzene	aromatic	opbV	<0.25	0.051	0.234	0.031 J
1-Methyl-4-N-Propylbenzene	aromatic	opbV	<0.25	<0.025	0.179	<0.025
Benzene	aromatic	ppbV	0.44D	0.071	0.229	0.043
Ethylbenzene	aromatic	ppbV	0.24 JD	0.061	0.969	0.048
Indane	aromatic	ppbV	<0.25	<0.025	0.185	< 0.025
Indene	aromatic	ppbV	<0.25	<0.025	<0.025	<0.025
Isopropylbenzene	aromatic	ppbV	0.1 JD	<0.01	0.289	<0.01
n-Butylbenzene	aromatic	ppbV	<0.25	<0.025	0,166	<0.025
N-Pentylbenzene	aromatic	ppbV	<0.25	<0.025	0,051	<0.025
n-Propylbenzene	aromatic	ppbV	<0.1	<0.01	0.495	0.019 J
o-Xylene	aromatic	ppbV	0.63D	0.612	1.76	0.167
p/m-Xylene	aromatic	ppbV	0.89D	0.24	3.53	0.174
sec-Butylbenzene	aromatic	ppbV	<0.25	<0.025	0.213	<0.025
Styrene	aromatic	ppbV	<0.1	0.063	0.125	0.074
Toluene	aromatic	ppbV	2.94D	0.266	1.68	0.208
1-Methylnaphthalene	naphthalene	ppbV	<0.5	<0.05	0.061 J	<0.05
2-Methylnaphthalene	naphthalene	ppbV	<0.5	<0.05	0.121 J	< 0.05
Naphthalene	naphthalene	ppbV	<0.25	0.066 B	0.266	0.061 B
Fertiary Butanol	alcohol	ppbV	3.88D	11.3	1.65	1.28
Ethyl-Tert-Butyl-Ether	ether	ppbV	0.56D	2.48	0,361	0.173
sopropyl Ether	ether	ppbV	<0.1	<0.01	<0.01	<0.01
Methyl tert butyl ether	ether	ppbV	<0.1	0.352	0.038	< 0.01
Tertiary-Arnyl Methyl Ether	ether	ppbV	<0.1	0.06	<0.01	<0.01
2-Ethylthiophene	thiophene	ppbV	<0.1	<0.01	<0.01	<0.01
2-Methylthiophene	thiophene	ppbV	<0.1	<0.01	<0.01	<0.01
3-Methylthiophene	thiophene	ppbV	<0.1	<0.01	<0.01	<0.01
Benzothiophene	thiophene	ppbV	<0.5	<0.05	<0.05 <0.01	<0.05
Thiophene	thiophene	ppbV	<0.1	<0.01	<0.01	<0.01
1,2-Dibromoethane	other	ppbV	<0.1	<0.01		<0.01
1,2-Dichloroethane	other	ppbV ppbV	<0.1 <0.5	<0.01 <0.05	<0.01 <0.05	<0.01 <0.05



# ATTACHMENT B.3.4: SOIL VAPOR AND GROUNDWATER MONITORING WELL HEADSPACE SAMPLE ANALYTICAL RESULTS Red Hill Bulk Fuel Storage Facility, Joint Base Pearl Harbor-Hickam, O'ahu, Hawai'i

	Lab S Sample D	ample ID: ate/Time:	£1740493-19 2017-10-30 9:12	L1740493-20 2017-10-26 10:03	L1740493-21 2017-10-26 11:38	L1740493-22 2017-10-26 15
		Matrix:	HEADSPACE	HEADSPACE	HEADSPACE	HEADSPACE
OCs BY USEPA METHOD TO-15 ( -Bulanol	TENTATIVELY IDENTIF	IED COM ppbV	POUNDS)	-	_	
-Hexanol, 2-ethyl-	alcohol	ppbV		-	-	<u> </u>
mylene Hydrate lethyl Alcohol	alcohol alcohol	ppbV	-	3.75 4.2	2.21	3.69
nknown	alcohol	ppbV ppbV		4.2	<u> </u>	3.08
nknown	alcohol	ppbV			-	
nknown nknown	alcohol alcohol	ppbV ppbV	-	-	-	
nknown alcohol	alcohol	ppbV			-	
nknown alcohol nknown	alcohol alcohol cycloalkane	ppbV ppbV	•	6.39		-
ropane	alkane	ppbV	-			
nknown nknown	alkane alkane	ppbV ppbV		2.41		
nknown alkane	alkane	ppbV		2.71	2.03	-
nknown alkane Pentene, 2-methyl-	alkane alkene	ppbV ppbV	-			-
4-Dimethyl-1-heptene	alkene	ppbV		4	*	-
nknown	alkene	ppbV		-	-	
nknown nknown	alkene alkene	ppbV ppbV				
nknown	alkene	ppbV			-	-
riknown nknown	alkene alkene	ppbV ppbV	-	<del></del>	-	-
nknown	alkene	ppbV	***************************************	-		
nknown nknown	alkene alkene	ppbV ppbV	-	-	-	
iknown	alkene	ppbV		5.91		
nknown nknown	alkene alkene	ppbV ppbV		-	4.28	-
nknown	alkene	ppbV	-			-
nknown	alkene	ppbV				
nknown nknown	alkene alkene	ppbV ppbV		-		-
iknown alkane	alkene	ppbV	-			
known alkene known alkene	alkene alkene	ppbV ppbV	-	•	*	
nknown	aromatic	ppbV	-	-	_	-
nknown exane, 2,3-dimethyl-	aromatic branched alkane	ppbV ppbV	-			-
nknown	branched alkane	ppbV	-	-	-	
known	branched alkane	ppbV	-	-	-	-
iknown iknown	branched alkane branched alkane	Vdqq	-	-	-	-
known alkane	branched alkane	ppbV		-	5.11	
iknown alkane iknown alkane	branched alkane branched alkane	ppbV ppbV		8.25 -	-	2.37
yclohexane, 1,1,3-trimethyl-	cycloalkane	ppbV		-	-	-
nknown nknown	cycloalkane cycloalkane	ppbV	-		***************************************	-
nknown	cycloalkane	ppbV ppbV	-		-	
nknown	cycloalkane	ppbV				-
nknown nknown	cycloalkane cycloalkane	ppbV ppbV		7.71	1.94	
nknown	cycloalkane	ppbV	*	~		
nknown nknown	cycloalkane cycloalkane	ppbV ppbV	-	-	-	-
nknown	cycloalkane	ppbV	-		-	-
nknown	cycloalkane	Vdqq		-	-	-
iknown alkane iknown cycloalkane	cycloalkane cycloalkane	ppbV ppbV	-	*	-	
known cycloalkane	cycloalkane	ppbV	-	-		
known cycloalkane known cycloalkane	cycloalkane cycloalkane	ppbV ppbV			-	<u> </u>
ran, tetrahydro-	furan	ppbV	-	-		
Butanone	ketone	ppbV	-		-	-
etone /clohexanone	ketone ketone	ppbV ppbV			-	2.98
clopentanone	ketone	Vdqq			-	
iknown iknown	ketone ketone	Vdqq Vdqq		-	-	3.87
known	ketone	Vdqq	-	-	-	
nknown nknown	ketone ketone cycloalkane	ppbV ppbV				
known	ketone cycloalkane	Vdqq				
known	ketone cycloalkane	ppb∀		-	-	-
iknown iknown	naphthalene other	ppbV ppbV				
known	other	Vdqq	-	-	2.23	
oknown oknown	other other	ppbV ppbV	-	-	-	
known	other	Vdqq			-	
nknown nknown	other other	ppbV ppbV	-	3.72	2.1	
iknown	other	Vaqq	-	94.1	94.6	212
nknown	other	ppbV	8220	13	39.8	20.6
nknown nknown	other other	ppbV ppbV	*	2.29	2,29 2,31	
nknown	other	Vdqq	•	•	-	3.3
nknown yclotrisiloxane, Hexamethyl-	other siloxane	Vdqq	-		-	-
ianol, Trimethyl-	siloxane	ppbV				<u> </u>
nknown	siloxane	ppbV			-	
known siloxane known siloxane	siloxane siloxane	ppbV ppbV	-	-	-	
known siloxane	siloxane	ppbV	-		-	
known siloxane	siloxane	ppbV ppbV				-
known siloxane	siloxane					

# ATTACHMENT 4

Navy CSM Interpretations of Thermal Profiles and Location of LNAPL (see footnote 1 above)

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3

4

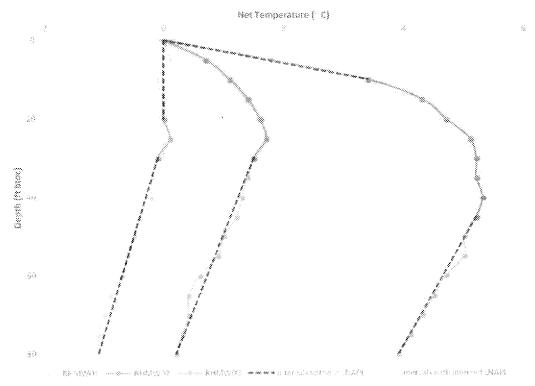
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This is highlighted on Figure 2-4, which shows the net temperature profile for each of the three wells, assuming an identical surface temperature (i.e., net temperature of 0 at the floor of the lower tunnel). The intervals in each profile that have constant slopes (i.e., no LNAPL) are highlighted with dashed lines, and the areas with changing slopes (due to heat generation associated with biodegradation of petroleum) are shaded. For each temperature profile, the depth intervals with constant slopes (no LNAPL) and the depth interval with changing slope (LNAPL) were identified using professional judgement based on visual inspection of the temperature profile. These intervals are shown in Table 2-1.



#### Notes:

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1. Grey shading shows interval of heat generation indicating presence of LNAPL within this interval.

2. Depths to water for the wells shown are as follows: RHMW01: 83.7 ft btoc; RHMW02: 86.4 ft btoc; RHMW03: 102.6 ft btoc.

Figure 2-4: Net (Background-Corrected) Temperature Profiles for Facility Wells (Well Air Temperature Measurements)

Table 2-1: Inferred LNAPL-Containing Intervals Indicated by Net (Background-Corrected) Temperature Profiles from Three Facility Monitoring Wells

Manitoring Well	Top of Casing Elevation (ft msl)	Approximate Top of LNAPL (ft btoc)	Approximate Bottom of LNAPL (ft bloc)	Approximate Top of LNAPL (ft msl)	Approximate Bottom of LNAPL (ft msl)
RHMW01	102.00	20	30	82	72
RHMW02	104.60	0	30	105	75
RHMW03	120.90	10	45	111	76

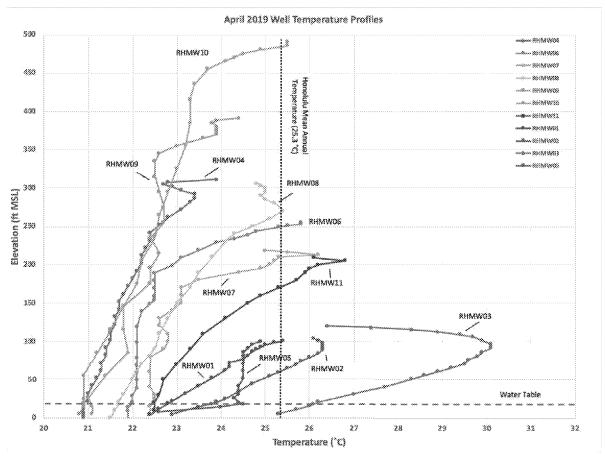
Note: All three wells are installed in the lower tunnel of the Facility.

- 1 results indicated that the two measurement methods yield comparable results. Thus, for the April
- 2 2019 field program, only Well Air Temperature measurements were collected. The Well Air
- 3 Temperature method is much simpler to implement.
- 4 For this measurement method, the thermocouple was fed through a hole in a well plug, a weight was
- 5 attached to a line attached to the end of the thermocouple, and the assembly was fed down the well.
- 6 The weight ensured the thermocouple wire stayed taut as temperature measurements were collected
- at 5-ft intervals down to the water table, then at the top, middle, and bottom of the water column. The
- 8 weight and thermocouple were decontaminated with Alconox and water between each well, and a
- 9 new line was used for each well.

#### 1.5 MEASUREMENT RESULTS

- Temperature measurements from the April 2019 event are provided on Figure 1-2 and in Attachment
- 12 E.1.1.

10



13 Figure 1-2: Well Temperature Profiles Measured April 2019

#### 14 2. NSZD Rates at Tunnel Wells

- 15 For the Tunnel Wells, NSZD rates for the April 2019 field event were calculated using the
- Background-Corrected Net Temperature method, the primary calculation method used for evaluation
- of the measurements from the first field event.

# ATTACHMENT 5

Honolulu Board of Water Supply Comments on Navy CSM (2019)

#### **BOARD OF WATER SUPPLY**

CITY AND COUNTY OF HONOLULU 630 SOUTH BERETANIA STREET HONOLULU, HI 96843 www.boardofwatersupply.com



KIRK CALDWELL, MAYOR

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ROSS S. SASAMURA, Ex-Officio JADE T. BUTAY, Ex-Officio

ERNEST Y. W. LAU, P.E. Manager and Chief Engineer

ELLEN E. KITAMURA, P.E. Deputy Manager and Chief Engineer

Mr. Omer Shalev EPA Red Hill Project Coordinator United States Environmental Protection Agency Region IX 75 Hawthorne Street San Francisco, California 94105

and

Ms. Roxanne Kwan Solid and Hazardous Waste Branch State of Hawaii Department of Health 2827 Waimano Home Road Pearl City, Hawaii 96782

Dear Mr. Shalev and Ms. Kwan:

Subject: Honolulu Board of Water Supply (BWS) Comments on the Navy's Conceptual

Site Model (CSM), Investigation and Remediation of Releases and Groundwater

Protection and Evaluation, Red Hill Bulk Fuel Storage Facility (RHBFSF)

Revision 1 dated June 30, 2019

The BWS has reviewed the above-referenced report and offers the following comments. Please note that BWS has submitted letters in the past that commented on previous versions of the CSM submitted by the Navy under RHBFSF Administrative Order on Consent (AOC) Section 6 (BWS, 2015; BWS, 2016a; BWS, 2016b; BWS, 2016c; BWS, 2016d; BWS, 2017a; BWS, 2017b; BWS, 2017c). We are referencing these past letters as they provide context and historical perspective to our comments contained herein.

#### General Comments on Navy's Revised CSM Report

The purpose of preparing a RHBFSF CSM is to provide a basis for evaluating groundwater flow, behavior of contaminants in the environment, contaminant transport pathways, and the potential for exposure of human receptors to drinking water potentially impacted by fuel releases from the facility. Our overall assessment is that the Navy's latest version of its CSM still does not provide an adequate basis for developing a groundwater flow model, nor should it be used to support an evaluation of contaminant transport pathways and the potential for receptor exposure. To the contrary, several of the key findings presented in the CSM are either unsupported or contradicted by available evidence. The Navy's most recent CSM report (DON, 2019) was also intended to address deficiencies in the prior version of its CSM (DON, 2018) identified by the

United States Environmental Protection Agency (EPA) and Hawaii Department of Health (DOH) (collectively, "Regulatory Agencies"). However, the Navy's revised CSM report fails to properly address many of the concerns raised about the prior version of the CSM by the Regulatory Agencies (EPA and DOH, 2018) and by the BWS (BWS, 2018a). As a result, many of the concerns previously raised by the Regulatory Agencies and the BWS remain valid.

In short, the Navy's revisions to its CSM are insufficient to render it useful for purposes of providing an accurate description of relevant site features and the surface and subsurface conditions or understanding the extent of identified contaminants of concern and the risk they pose to critical receptors like Halawa Shaft. Consequently, neither the report's findings nor the Navy's conclusions can be used to inform a potential tank upgrade alternative (TUA) unless and until these flaws are corrected. We request that the Regulatory Agencies reject the Navy's revised CSM report and take all steps necessary to protect our drinking water by requiring that the Navy upgrade the RHBFSF tanks with secondary containment or relocate them away from our sole-source groundwater aguifer.

## History of CSM Development and Regulatory Concerns

The Navy's revised CSM report (Revision 01), dated June 30, 2019, is a modification of the Navy's prior CSM (Revision 00), dated July 27, 2018. Both CSM documents consist of seven modules that purport to describe the physical setting in Moanalua and Halawa Valleys, RHBFSF construction and operation, past releases and migration of light non-aqueous phase liquid (LNAPL), conceptual models of the vadose zone (subsurface between ground level and the water table) and saturated zone (subsurface below the water table), fate and transport of dissolved and LNAPL contamination, and a model for exposure to fuel contaminants.

The Navy received comments from the BWS, dated October 24, 2018 (BWS, 2018a), and from the Regulatory Agencies, dated October 29, 2018 (EPA and DOH, 2018), and DOH, dated July 1, 2019 (DOH, 2019a) regarding specific inadequacies of the Navy's CSM Revision 00. Among the EPA, DOH, and BWS there was a general consensus that certain interpretations and determinations included in the Navy's CSM Revision 00 (DON, 2018a) were premature and/or inappropriate. For example, the Regulatory Agencies' expressed the following initial concerns with the Navy's CSM Revision 00 in October 2018:

- "Predominant strike and dip of basalt in the geologic model: the direction and magnitude as represented by the Navy thus far do not agree with the lava flow geometry independently evaluated by the Regulatory Agencies and provided to the Navy. This information is important because it will influence Navy's conclusions regarding groundwater flow paths and transport" (EPA and DOH, 2018).
- "Saprolite extent in the interim model vs. depths inferred by seismic profiling: the extent of the modeled saprolite/basalt interface depths do not agree with the seismic profiling. In particular, the seismic profiling indicates that the saprolite layer depth in the upper reaches of the Halawa Valleys constitutes a much less protective barrier to northwest groundwater flow than the (Navy) groundwater flow model (GFM) indicates. This directly impacts the evaluation of risk to the Halawa Shaft" (EPA and DOH, 2018).

"Preferential pathways: the consideration and methods of incorporation of preferential pathways in both the Navy CSM and the GFM are unclear. Although it is impracticable to precisely characterize these features, the influence that geologic structures, such as voids, fractures, lava tubes, and the permeable interface between lava flows, have on contaminant and groundwater transport should be explained conceptually in the CSM. The influence of these structures should also be incorporated into the GFM using appropriate and traceable mathematical representations. This directly impacts the Navy's ability to evaluate contaminant transport in the vadose zone and in the groundwater" (EPA and DOH, 2018).

In its July 2019 evaluation of the groundwater flow paths in the Moanalua, Red Hill, and Halawa regions, the DOH listed several still-outstanding issues with the Navy's CSM and the Navy's groundwater flow model that need resolution, including:

- The disparity between the measured and modeled groundwater gradient along the axis of Red Hill Ridge and its implications for a reliable CSM and numerical groundwater flow model;
- The absence of supporting field data for the CSM-assumed primary groundwater flow direction toward the southwest and away from Halawa Shaft (one of the key receptors of concern);
- Overestimation of the resistance to northwest groundwater flow posed by the lower-permeability materials (valley fill and saprolite) given seismic study indications that the valley fill/saprolite likely poses little resistance to groundwater flow in the South Halawa valley adjacent to the underground storage tanks (USTs) and in North Halawa valley adjacent to Halawa Shaft; and,
- Lack of consideration of groundwater flow toward the northwest without providing a compelling rationale (DOH, 2019a).

As a result, the Regulatory Agencies requested that the Navy address these concerns and revise its CSM. The Navy's revised CSM report states that a primary goal of the CSM Revision 01 is to address the Regulatory Agencies' comments to the CSM Revision 00. Despite this stated goal, the revised Navy's CSM does not address many of these comments. Accordingly, the BWS requests that the Regulatory Agencies direct the Navy to provide a separate written response to each comment and supplement any inadequate response, and that the Regulatory Agencies provide either an approval or disapproval of such responses in writing. Unless and until the Navy has adequately addressed all outstanding CSM comments, the Regulatory Agencies should not allow the current CSM to inform a potential TUA decision. In the absence of an adequate CSM, and in order to protect Oahu's critical drinking water supply, the Regulatory Agencies should require the Navy to either relocate the RHBFSF tanks away from our sole source groundwater aquifer or, at a minimum, upgrade the tanks with secondary containment. The revised CSM is inadequate in several areas as follows.

### **Uncertainty and Potential Bias**

The revised CSM fails to provide a proper assessment of the significant uncertainty associated with the Navy's characterization of the groundwater flow system and of the nature and extent of groundwater contamination at the RHBFSF. In fact, key analysis associated with the most basic aspects of the uncertainty with groundwater flow systems remain unresolved. For example, nowhere in the CSM does the Navy address the fundamental problem of a lack of an adequate monitoring well network for monitoring water levels and groundwater contamination near the fuel tanks. Although EPA guidelines (EPA, 1988; EPA, 1989) do not specify the number of monitoring wells needed to adequately characterize the groundwater flow system and contaminant plume extent, they clearly indicate the density of monitoring well networks should increase with the hydrogeological complexity of a site. Without a sufficient number of monitoring wells in the right locations, the ability to estimate groundwater flow directions and the properties of contaminant plumes will be subject to considerable uncertainty.

The Navy is essentially relying on data from three monitoring wells (RHMW-01, RHMW-02, and RHMW-03) within 450 feet of the twenty RHBFSF tanks, which is far too sparse a monitoring well network for a facility with such a large fuel storage capacity and complex subsurface geology. The BWS offered suggested monitoring well locations to the Regulatory Agencies and the Navy several years ago to try to mitigate this concern (BWS, 2016b). The BWS proposed, as a starting point only, that at least twelve monitoring wells be added within 50 feet of the tanks to monitor both groundwater and soil vapor (BWS, 2016b). The BWS suggested the additional data from these new wells be used to evaluate the locations for additional wells. The BWS also suggested a process (decision tree) to address how decisions would be made for additional well locations and well installation order based on new data (BWS, 2016a), but to date the Navy has neither implemented these recommendations nor provided a reasonable justification for its current approach.

The sparse monitoring well network used by the Navy to measure water levels and groundwater contamination is a major contributor to this uncertainty. Given the subsurface conditions in the vicinity of the RHBFSF, where LNAPL migration occurs in a highly heterogeneous basalt containing preferential flows, the BWS believes that the Navy's current monitoring well network is inadequate and should be addressed as a major source of uncertainty in the CSM. Because of the considerable uncertainty associated with much of the analysis in the CSM, the BWS recommends that the Navy revise the CSM be compliant with ASTM Guide D5447-92, which states:

"Provide an analysis of data deficiencies and potential sources of error with the conceptual model. The conceptual model usually contains areas of uncertainty due to a lack of field data. Identify these areas and their significance due to a lack of field data. Identify these areas and their significance to the conceptual model evaluated with respect to the project objectives. In cases where the system may be conceptualized in more than one way, these alternative conceptual models should be described and evaluated" (ASTM, 1999).

Even where recent studies shed light on the uncertainties regarding groundwater flow, the Navy's revised CSM fails to adequately incorporate them. Section 2.14 "Addressing Uncertainty" of the CSM states:

"Resolving uncertainty regarding groundwater levels and hydraulic gradients in the site vicinity is an important objective of recently completed, ongoing, and planned investigation. These investigations include the well elevation survey and the gyroscope survey for Red Hill groundwater monitoring wells, synoptic water level measurement recently collected by the United States Geological Survey (USGS) and installation of new monitoring wells at Red Hill and in North and South Halawa Valleys" (DON, 2019) (citations omitted).

The BWS is concerned that despite the CSM having been released a year after the completion of the three studies referenced above, the Navy's CSM does not provide any flow directions based on this data. This critical omission should be deemed unacceptable by the Regulatory Agencies given the fact that both the BWS and the Regulatory Agencies have been able to produce maps of hydraulic contours using the USGS synoptic data.

Finally, based on our review of the data, the Navy's revised CSM appears biased to promote site conditions and processes that would favor a conclusion that there is a low risk of groundwater contamination from a fuel spill. For example, with respect to groundwater flow, the CSM treats basalt as an equivalent homogeneous media, assumes that valley fill and/or saprolite acts as an effective barrier to shallow groundwater flow, and concludes that groundwater flow is primarily from mountain (mauka) to the ocean (makai).

An important set of alternative conceptual models that should be identified and discussed by the Navy in its CSM are those that would lead to a more conservative prediction of risks to the sole-source aquifer. Examples of alternative conceptual models for the groundwater flow system that the BWS recommends consideration are the following:

- In the vicinity of RBHFSF, a principal component of groundwater flow is toward the northwest.
- The groundwater flow and transport in the basalt cannot be treated as an equivalent porous media (EPM) and groundwater flow is principally within preferential flow paths define by the interconnection of clinker zones. The measured water levels in the upper 30 feet of the basalt is not reflective of the groundwater flow system at depths greater than 100 feet.

The Navy's apparent bias in interpreting site data is particularly evident in its development of a clinker-zone model, which is discussed in greater detail below. This model, which was presented to the public as representative of site conditions, includes locating a single clinker zone along the axis of RHBFSF that provides a preferential pathway to Red Hill Shaft. This clinker-zone model effectively manufactures hydrogeological conditions that would act like a conduit for draining shallow groundwater from beneath the fuel tanks to Red Hill Shaft. The Navy continues to advocate for this model even though the physical attributes of the clinker zone are physically and geologically implausible and the simulated hydraulic gradients are opposite of the direction indicated by the measured hydraulic gradients. Simply put, the clinker-zone model is unrealistic and inconsistent with existing site data.

### Characterization Hydrogeology

The Navy's revised CSM is deficient in its characterization of certain important site features and conditions, most notably hydraulic gradients and the aquifer properties of preferential flow and saprolite. These features and conditions are important because they largely determine groundwater flow direction and groundwater flow velocity.

#### Hydraulic Gradients

A major issue with the Navy's interim groundwater model has been its inability to reproduce the direction and magnitude of the measured hydraulic gradients. This issue is caused by, at least in part, the model's reliance on certain CSM findings that are unsupported and/or contradicted by available evidence. As stated by DOH and previously discussed by this letter, a major point of disagreement between the Regulatory Agencies and the Navy's current CSM and interim groundwater flow model is the groundwater flow direction in the vicinity of the RHBFSF tanks (DOH, 2019a). The key disparity is that where the modeled groundwater gradients are principally along the axis of Red Hill ridge the measured groundwater gradients are principally across the axis of the Red Hill ridge.

Unfortunately, the CSM Revision 01 does not resolve these issues. To address these concerns, the Navy needs to further revise the CSM to provide a detailed analysis of the measured hydraulic gradients, to determine to what extent the hydraulic gradients can be characterized by horizontal gradients, and to provide maps of flow lines as specified by ASTM Guide D5447-92 (ASTM, 1999), which is titled "Application of a Ground-Water Flow Model to a Site-Specific Problem." This standard specifies that the analysis of the flow system must include "the assessment of vertical and horizonal gradients, delineation of ground-water divides, and mapping of flow lines."

As a result of concerns raised by Regulatory Agencies and the BWS, the Navy has changed several declarative assertions regarding groundwater flow directions included in the previous CSM to statements of "likely" conditions in its current CSM. Two examples of these revisions are:

- "General transport of COPCs [contaminants of potential concern] in the dissolved plume is in the southwest direction toward Red Hill Shaft" (DON, 2018a) (emphasis added) was changed to "General transport of COPCs in the dissolved plume is expected to be in the southwest direction toward Red Hill Shaft" (DON, 2019) (emphasis added).
- 2. "Migration to the southeast and northwest **is** limited by the extent of lower permeability material" (DON, 2018a) (emphasis added) was changed to "Migration to the southeast and northwest **is expected to be** limited by the extent of lower-permeability material" (DON, 2019) (emphasis added).

Based on our review of the data, these changes do not sufficiently address the considerable deficiencies raised by the Regulatory Agencies and the BWS about the Navy's assessment of the actual data. For example, despite having over a year to update the analysis of water level data, the revised CSM does not provide a single map showing groundwater contours of water levels and inferred groundwater direction based on the 2017-2018 synoptic monitoring event.

Throughout the revised CSM, the Navy attempts to justify its decision not to map contours of water levels by claiming that because of the highly permeable basalt, the water table is flat and hydraulic gradients cannot be determined with great confidence. This is not supportable and the BWS, the EPA and DOH all concur that mapping contours here is possible (BWS, 2019; EPA and DOH, 2018).

In both the revised CSM and the prior version, the Navy presents the measured water levels in wells during the 2017-2018 synoptic water level survey but does not include contours of water levels. Figures 1 through 4 below provide the missing contours for four dates using water levels uncorrected for barometric pressure. Despite the relatively flat water levels, the water table contours interpolated from the measured water levels provide a very consistent set of results for the four dates. Most notably, all four figures show a much larger hydraulic gradient to the northwest than the southeast at the RHBFSF. It should also be noted that the results in Figures 1 through 4 are very similar whether or not the water levels are corrected for barometric pressure.

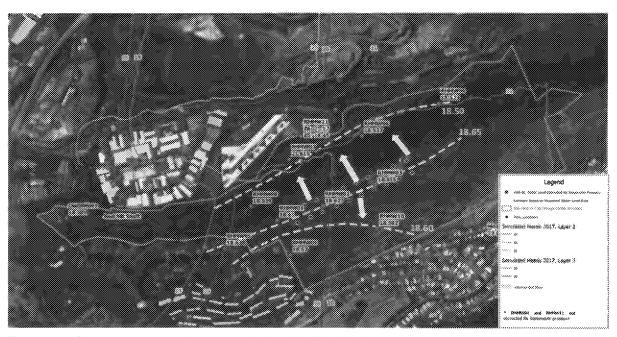


Figure 1 Measured water levels at 01/15/2018 6:00 after Red Hill Shaft has been not pumping for five days

Source: Honolulu Board of Water Supply (BWS). 2019. Letter from BWS to EPA and DOH dated April 12, 2019. Subject: Board of Water Supply (BWS) Comments on the Red Hill Administrative Order on Consent (AOC) Statement of Work (SOW) Sections 6 and 7 Groundwater Modeling Working Group Meeting No. 14 held March 13, 2019

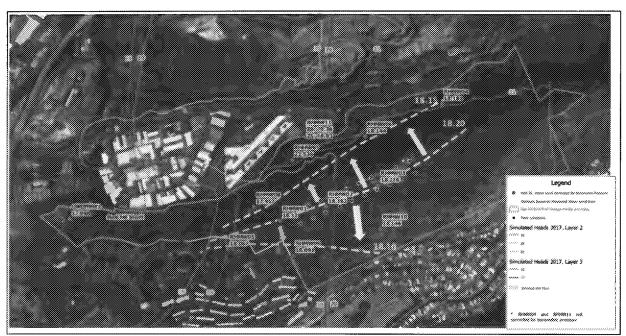


Figure 2 Measured water levels at 01/19/2018 21:00 after Red Hill Shaft has been pumping five days at 7.7 MGD

Source: Honolulu Board of Water Supply (BWS). 2019. Letter from BWS to EPA and DOH dated April 12, 2019. Subject: Board of Water Supply (BWS) Comments on the Red Hill Administrative Order on Consent (AOC) Statement of Work (SOW) Sections 6 and 7 Groundwater Modeling Working Group Meeting No. 14 held March 13, 2019

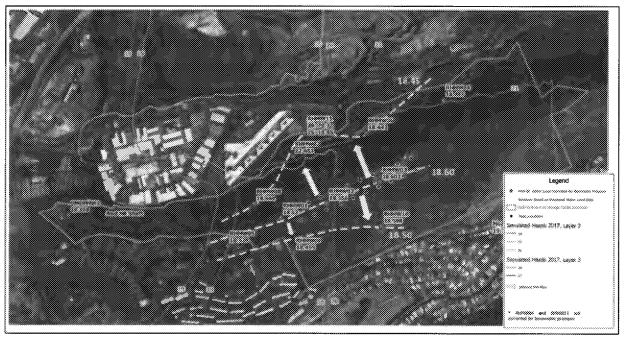


Figure 3 Measured water levels at 02/05/2018 19:00 after Red Hill Shaft has been pumping as usually and Halawa Shaft has not been pumping

Source: Honolulu Board of Water Supply (BWS). 2019. Letter from BWS to EPA and DOH dated April 12, 2019. Subject: Board of Water Supply (BWS) Comments on the Red Hill Administrative Order on Consent (AOC) Statement of Work (SOW) Sections 6 and 7 Groundwater Modeling Working Group Meeting No. 14 held March 13, 2019

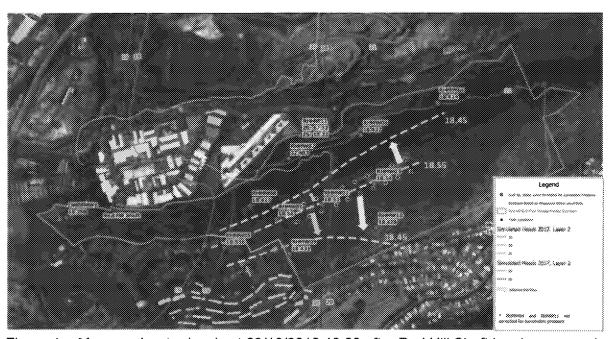


Figure 4 Measured water levels at 02/19/2018 13:00 after Red Hill Shaft has been pumping as usually and Halawa Shaft has maintained averaged pumping rate

Source: Honolulu Board of Water Supply (BWS). 2019. Letter from BWS to EPA and DOH dated April 12, 2019. Subject: Board of Water Supply (BWS) Comments on the Red Hill Administrative Order on Consent (AOC) Statement of Work (SOW) Sections 6 and 7 Groundwater Modeling Working Group Meeting No. 14 held March 13, 2019

Figure 5 was generated by the DOH and includes a greater area and a different set of contour intervals. Figure 5 demonstrates that the Navy's presumption that groundwater flow in the vicinity of the RHBFSF is from mountain (mauka) to ocean (makai) is not supported by the measured water levels. In its discussion of the hydraulic gradients, the DOH acknowledges that other modeling studies have also assumed mauka to makai flow in the Red Hill area. However, after their review of the measured water level the DOH states:

"The groundwater elevation contours beneath the Red Hill Ridge and beneath the Halawa-Aiea area indicate that at least where the penetration of the saprolite into aquifer is either shallow or non-existent, the relative groundwater elevations indicate groundwater flow to the northwest. More specifically, the groundwater contouring strongly suggests that the flow direction beneath the upper part of the facility is to the northwest. This observation is in direct contrast to the Navy's expectation that the water flows along the shortest mauka to makai path from the high elevation recharge areas to the coast" (DOH, 2019a).

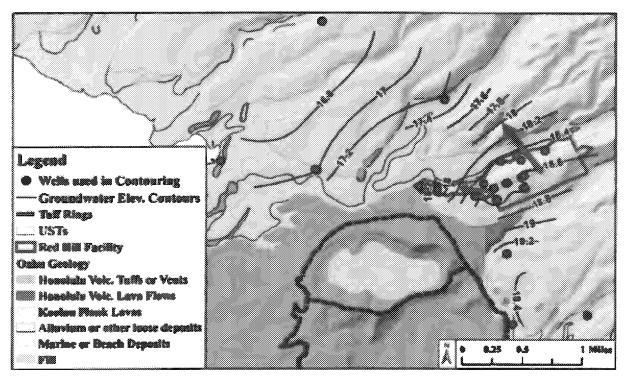


Figure 5 Water level contours interpolated from water levels measured at 2/05/2018 after pumping as usual and Halawa Shaft has not been pumping. Arrow indicated the implied groundwater flow directions based on groundwater elevation contours

Source: Department of Health, Safe Drinking Water Branch (DOH). 2019a. Hawaii Department of Health Evaluation of Groundwater Flow Paths in the Moanalua, Red Hill, and Halawa Regions, Revision 2 by Whitter, R.B., Thomas, D.M., and Becket, G.D. July 11.

It is clear to the BWS and consistent with comments from the Regulatory Agencies that the available evidence simply does not support the Navy's mauka to makai only groundwater flow regime. Despite all the analysis and data that has been presented to the Navy on this issue since its last CSM iteration, the revised CSM still does not appear to consider this information and does not meaningfully discuss any alternative conceptual models for the groundwater flow system. This is a critical flaw that undermines the Navy's entire analysis.

#### Aguifer Properties - Preferential Flows

The Navy's revised CSM presents considerable data that shows that preferential flow paths and zones of high permeability are not uncommon in the basalt. The Navy also states that interconnection of clinker zones represents the preferential flow paths that could account for a significant portion of groundwater flow. The BWS agrees that clinker zones provide preferential flow pathways for groundwater. However, after the Navy identifies clinker zones as being of paramount important to groundwater flow, the Navy goes on to promote conceptualizing and modeling the basalt as an EPM without describing how the preferential flow pathways could bias data analysis and risk predictions. The concerns that the BWS has with the current CSM are

consistent with comments prepared by Matt Tonkin (Tonkin, 2018), EPA, and DOH (EPA and DOH, 2018) regarding the previous CSM, which are:

"Studies from other basalt regions, however, indicate a high potential for connected flow-paths that can enhance migration distances and rates versus EPM assumptions: and, though few controlled experiments are published for conditions directly analogous to Red Hill, studies in simpler environments show heterogeneous migration even under ideal conditions. At Red Hill, the documented geology, stratigraphic exposures in the nearby quarry, and variable hydraulic gradients indicate the subsurface is more complex than the current CSM and groundwater model represent" (Tonkin, 2018).

"The consideration and methods of incorporation of preferential pathways in both the CSM and the groundwater model are unclear. Although it is impracticable to precisely characterize these features, the influence that geologic structures, such as voids, fractures, lava tubes, and the permeable interface between lava flows, have on contaminant and groundwater transport should be explained conceptually in the CSM. The influence of these structures should also be incorporated into the GFM [groundwater flow model] using appropriate and traceable mathematical representations. This directly impacts the Navy's ability to evaluate contaminant transport in the vadose zone and in the groundwater" (EPA and DOH, 2018).

In July 2019, the Regulatory Agencies expressed significant concerns that the Navy has prematurely dismissed the importance of preferential pathways and presumed that the basalt could be modeled as an EPM:

"[I]t is typical in scientific literature that the character of the host rock is demonstrated to be reasonably approximated at relevant scales using an EPM. This has not yet been demonstrated at Red Hill. The agencies have noted in past comments that aspects of the fractured and void-influenced system need to be quantified as an initial basis to understand the scale and behavior of LNAPL and associated contaminant transport in this system.

. . .

If it can be demonstrated that the character of the void/fracture structure at Red Hill can be reasonably approximated at relevant scales using an EPM assumption, it is then necessary to develop parameters for the distributed porous media model that reasonably represent the movement of fluids through the host rock" (DOH and EPA, 2019) (citation omitted).

During Groundwater Modeling Working Group Meeting No. 14 (March 2019) the Navy stated that it would continue with a clinker-zone model and will also construct a "heterogeneous" model. The results of the Navy's clinker-zone model are cited throughout the revised CSM and were presented in a November 2018 Honolulu City Council meeting to demonstrate the Navy's interim model is adequately predicting groundwater levels. As previously discussed by BWS, the Navy's clinker-zone model and its simulated water levels is physically implausible and

inconsistent with field data and therefore should not be considered as a viable model (BWS, 2019).

The clinker model scenario is shown in Figure 6, a sole clinker is located within only model layer 2 and within a narrow lateral zone that is aligned with the location of the fuel tanks and provides a connection to Red Hill Shaft. The dip angle and thicknesses required to create the clinker realization in Figure 6 is physically unrealistic and incompatible with the CSM data included as part of the geological cross-section shown in Figure 7. To generate a flat hydraulic gradient the hydraulic conductivity of the clinker was set to 250 times greater than the basalt. Figure 8 shows the flat hydraulic gradient simulated by the clinker-zone model. The contours show that the hydraulic gradient is toward the middle of the topographic ridge, which is the opposite direction of the measured hydraulic gradient (also see Figures 2 and 3) (BWS, 2018d).

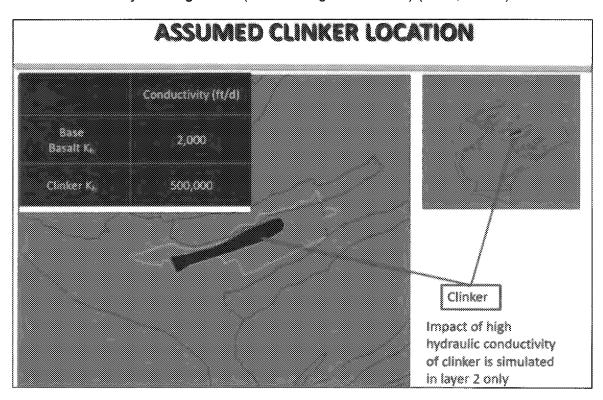


Figure 6. Location and hydraulic properties associated with Clinker Zone depicted in the Navy's Conceptual Clinker Model (modified from slide presented by the Navy on March 16, 2018 during Groundwater Modeling Working Group Meeting No. 9)

Source: Honolulu Board of Water Supply (BWS). 2018d. Letter from BWS to EPA and DOH dated April 24, 2018. Subject: Honolulu Board of Water Supply (BWS) Comments on the Red Hill Administrative Order on Consent (AOC) Statement of Work (SOW) Sections 6 and 7 Groundwater Modeling Working Group Meeting No. 9 Held March 16.

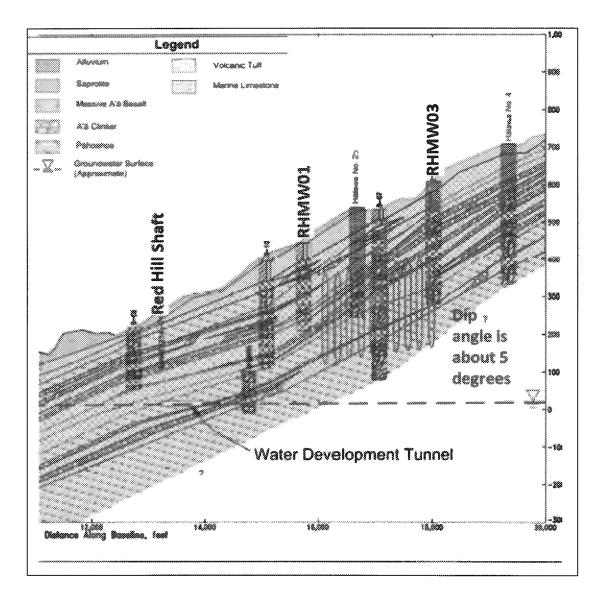


Figure 7. Mapped Basalt Zones showing dipping clinker zones in the vicinity of Red Hill Shaft and monitoring wells RHMW01 and RHMW02 (DON, 2018a Figure 5-2).

Source: Department of the Navy (DON), 2018a. Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Storage Facility. Joint Base Pearl Harbor-Hickam, Oahu, Hawaii. July 27,2018 Revision 00, prepared by AECOM Technical Services, Inc.

Neither the Navy's revised CSM nor its groundwater flow model can be relied upon to support a TUA decision. Moreover, the CSM cannot be considered to be complete unless and until the CSM provides, at a minimum, the geologic framework used to guide and constrain the location, size, and orientation of clinkers as well as the type and amount of aquifer heterogeneity ultimately incorporated into the Navy's groundwater flow model. The Navy's clinker-zone model does not satisfy this concern. To the contrary, the Navy's clinker-zone model and its simulated water levels is physically implausible and inconsistent with field data and, therefore, should not

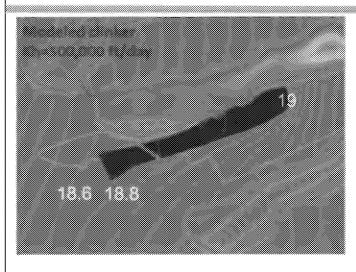
be considered as a viable model (BWS, 2019). While the BWS acknowledges that clinker zones represent preferential flow paths, there is no geological evidence that indicates that a single clinker zone connects the shallow groundwater flow zone beneath the tanks to Red Hill Shaft as presumed by the Navy's clinker-zone model. The revised CSM does not provide any geologic information from either the tank barrel logs or the monitoring well drilling logs to model a clinker zone as shown in Figure 6. Moreover, this model is inconsistent with available data that indicates thin clinker zones dip through multiple layers and are interconnected vertically by fractured basalt.

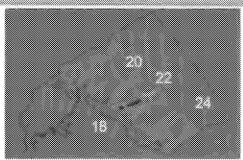
With regard to providing information to guide the development of alternative groundwater flow and transport models, the revised CSM is limited in that it does not:

- Provide the necessary geologic constraints needed to construct the groundwater flow models that the Navy has designated as the clinker-zone model and the heterogeneous model; and,
- 2. Provide the necessary information to describe quantify the potential impacts of preferential flow on groundwater transport.

The BWS recommends that the Regulatory Agencies require the Navy's CSM to include a detailed description of the Navy clinker-zone model because it is used to calculate biodegradation rates from measured concentration values in wells. The BWS also recommends that the Regulatory Agencies consider the CSM to be incomplete until it is modified to include hydrogeological constraints to guide the development of groundwater flow models to represent preferential flows and/or heterogeneity in the saturated basalt in the RHBFSF. The Navy should not be allowed to rely on the groundwater modeling for any decision unless and until it completes this analysis.

# SENSITIVITY TO HETEROGENEITY: PRESENCE OF CLINKER — WATER LEVELS IN LAYER 2





#### Key Observations:

- · Locally northwest flow towards clinker at Red Hill
- Good calibration statistics
- Very flat gradients in the clinker (~0.0001)

Figure 8 Simulated hydraulic heads produced by the Navy's Conceptual Clinker Model (modified from slide presented by the Navy on March 16, 2018 during a Groundwater Modeling Working Group Meeting No. 9)

Source: Honolulu Board of Water Supply (BWS). 2018d. Letter from BWS to EPA and DOH dated April 24, 2018. Subject: Honolulu Board of Water Supply (BWS) Comments on the Red Hill Administrative Order on Consent (AOC) Statement of Work (SOW) Sections 6 and 7 Groundwater Modeling Working Group Meeting No. 9 Held March 16.

#### Aquifer Properties - Saprolite

The Navy's revised CSM incorrectly assumes that lower-permeability saprolite acts as an effective barrier to shallow groundwater flow. The depth of the saprolite/basalt interface is important in many areas of the model but is particularly important in the valley locations where the Navy's interim groundwater model has extended the saprolite/basalt interface below the water table. The BWS (BWS, 2018b, BWS, 2018c), EPA and DOH (EPA and DOH, 2018) review of available information in the CSM and the Navy Geophysical Seismic Report (DON, 2018c) indicates that the depth and hydraulic conductivity of the saprolite is highly uncertain and that the Navy's representation of the saprolite is unreasonably limited to deep below the water table and acting as barrier to groundwater flow across South Halawa Valley.

An overarching concern with the Navy's interpretation of the seismic data to create cross-sections are the numerous, unverified assumptions (BWS, 2018c) and that there is only one

control point. With an understanding of the limitation of the seismic data, the DOH (DOH, 2019a) used the six transects in Figure 9 to create a three-dimensional geologic model that maps the basalt/saprolite in North Halawa and South Halawa valleys. Based on the interpretations of the geologic model, the DOH concludes:

"The important conclusion of this saprolite/basalt interface depth evaluation is that the resistance to northwest groundwater flow posed by the valley fill/saprolite sequence is likely over-estimated by the Navy's current conceptual model. Extrapolations based on the seismic study indicates that the valley fill/saprolite sequence likely poses little resistance to groundwater flow in the South Halawa Valley adjacent to the USTs and in North Halawa valley adjacent to the Halawa Shaft" (DOH, 2019a) (emphasis added).

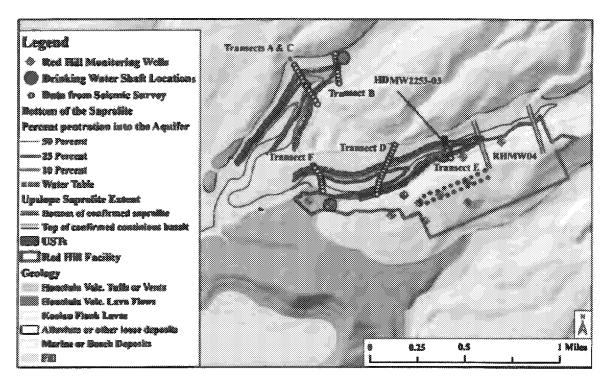


Figure 9 Estimated depth to which saprolite extends to the freshwater aquifer expressed as the percent of the total aquifer

Source: Department of Health, Safe Drinking Water Branch (DOH). 2019b. Hawaii Department of Health Evaluation of Groundwater Flow Paths in the Moanalua, Red Hill, and Halawa Regions, Revision 2 by Whitter, R.B., Thomas, D.M., and Becket, G.D. July 11.

The DOH used the six transects (shown in Figure 9) to calculate the slope of the basalt/saprolite interface. Its analysis of these six transects demonstrates that, except for the region between Transect F and Transect D, the dip angle for the basalt/saprolite interface is much greater than the 3% slope assumed by the Navy. In fact, the DOH analysis indicates that the dip angle for

the basalt/saprolite is 9.1% between Transect D and Transect E in South Halawa Valley and is 24% between Transect A and Transect B in North Halawa Valley.

Other important DOH findings include:

- "In North Halawa Valley, the deepest saprolite/Basalt interface depth estimated by seismic survey at Transect B was -20 ft msl. Projecting up North Halawa Valley the saprolite/basalt interface is estimated to rise above the water table slightly before the Halawa Shaft" (DOH, 2019b).
- "the 2015 and the 2017-2018 Synoptic Water Level Studies show that groundwater elevation at RHMW04 is about a foot higher than at the Halawa Shaft; and the groundwater elevation at OWDF-MW1 is 1.5 ft higher than at HBWS observation well T-45. With this difference in head across Halawa Valley and the limited saprolite penetration, groundwater almost certainly flows from Red Hill beneath and around the valley fill/saprolite sequence to the Halawa side of North Halawa Valley" (DOH, 2019b).
- "As noted in Section 6.1.4 of the CSM report (DON, 2018a), the hydraulic head in the basalt zones of RHMW11 generally define a downward gradient. This is consistent and would be expected for groundwater flowing to the northwest by passing under the saprolite/basalt interface. Figure 6-10 of the CSM report (DON, 2018a) shows that the groundwater elevation in RHMW11-Zone 5 is more than a foot higher than that at the Halawa Shaft when the pumps are off. As Figure [9] shows, the saprolite between RHMW11 and the Halawa Shaft extends much less than 25 percent into the aquifer, making well over 80 percent of the aquifer thickness available to transmit water from the Red Hill side of South Halawa Valley to the north side of North Halawa Valley" (DOH, 2019b).

Based on the findings from the EPA and DOH analysis of the seismic data (EPA and DOH, 2018; DOH, 2019b), the BWS recommends that the Regulatory Agencies require the CSM be considered incomplete until it is modified to include a similar evaluation as performed by the DOH and hydrogeologic constraints to guide the development of saprolite/basalt boundary in South Halawa and North Halawa valleys.

#### **Contaminant Transport**

A stated above, a significant problem with developing a CSM for the groundwater flow system at RHBFSF is the sparse well monitoring network. The importance of an adequate monitoring network is even more important when developing a CSM for groundwater contaminant transport. A common thread of concern that the BWS has with the Navy's entire discussion of groundwater transport and biodegradation is that the Navy's findings are based more on speculation and conjecture than logical deductions.

In the August 1, 2019 Groundwater Modeling Working Group Meeting No. 15, the DOH emphasized BWS concerns and with the following summary statements:

- There are substantial differences in the interpretation of available field data for the Red Hill Area (DOH, 2019a);
- These interpretations are the foundation for the risk analysis and levels of computed risks to Oahu's drinking water sources (DOH, 2019a); and,
- These differences, to a significant degree, are the results of the limited data set that is inadequate to definitely resolve rates and directions of groundwater flow (DOH, 2019b).

This problem could be addressed by the installation of additional wells and the Navy's sparse monitoring well network is a primary contributor to the difficulty associated with developing unique and technical defensible groundwater flow paths and exposure routes in the RFBFSF. For the 20 fuel storage tanks at Red Hill, there are only three monitoring wells within 450 feet of the tanks. As discussed in greater detail above, the need for more wells here is made critical due to the fact that groundwater flow is primarily controlled by preferential flow paths through clinker zones that have not be delineated by the Navy.

In Section 1.3 of the CSM, the Navy states that a primary goal of CSM Revision 01 is to address the Regulatory Agencies comments on the CSM Revision 00 provided in a letter dated October 29, 2018 (EPA and DOH, 2018). The Revised CSM, however, fails to address comments related to the fate and transport of groundwater contaminants. An examination of the Navy's calculation of biodegradation rates and the Navy's thermal Natural Source Zone Depletion (NSZD) investigation is illustrative.

#### **Biodegradation Rates**

The Navy's revised CSM improperly develops its biodegradation rates on modeling that is inconsistent with available data. The Navy assumes that monitoring wells RHMW01 and RHMW02 are aligned with a west-southwesterly groundwater flow path through the tank farm based on the fact that "the Navy current interim groundwater model and clinker-zone model indicates that they [the two monitoring wells] are on the same flow path" (DON, 2019). However, as discussed above, neither the Navy's current interim groundwater model nor the clinker-zone model provide acceptable matches to the measured water level data.

The biodegradation rates cannot be deemed reliable given that they are based on results from models that do not provide reasonable matches to the measured differences in water levels. Therefore, BWS asks that the Regulatory Agencies consider the CSM incomplete and unacceptable for supporting any groundwater transport modeling until the Navy has fully addressed both BWS and Regulatory Agency concerns regarding the calculation of biodegradation rates.

#### Thermal NSZD Investigation

The Navy's revised CSM has not addressed previous comments regarding the Navy's underlying assumption that an increase in the temperature profile can be used to determine the vertical distribution of LNAPL in the vadose zone. The Navy makes this assertion without offering sufficient evidence to establish the relationship. The BWS (BWS, 2018a), EPA, and

DOH, have questioned the validity of the Navy's critical assumption (EPA and DOH, 2018). The Regulatory Agencies have stated:

"A net positive temperature profile indicates the effects of exothermic biologic reactions and is affected by a variety of subsurface factors. In general, that relationship can be useful to infer lateral distributions of LNAPL biodegradation but is highly uncertain with respect to the LNAPL vertical distribution. In many cases, as shown in the example thermal profile in our August 15, 2018 presentation (reproduced as Figure 10), the LNAPL vertical mass distribution cannot be inferred from the temperature profile. A review of data in the 2007 Red Hill investigation report (DON, 2007) shows that the rock cores were evaluated at well RHMW02 for evidence of petroleum contamination by checking for odor and by screening with a photo-ionization detector. No evidence of petroleum contamination was found" (EPA and DOH, 2018).

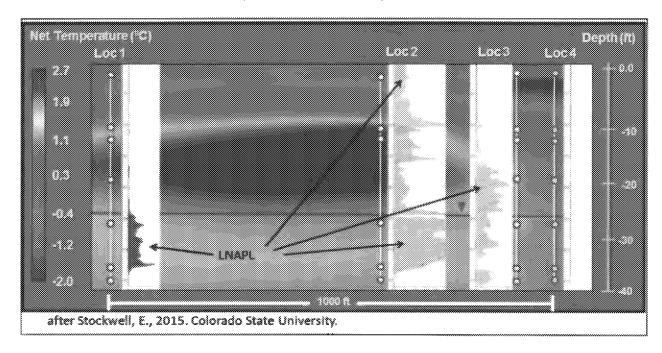


Figure 10 Result from a field study presented by EPA and DOH on August 15, 2018 that shows that there is not a correlation between temperature change in the vadose zone and the presence of LNAPL

Source: U.S. EPA and Hawaii Department of Health (EPA and DOH). 2018. "Approval to revise schedule for deliverables 6.3 - Investigation and Remediation of Releases Report and 7.1.3. - Groundwater Flow Model Report of the Red Hill Administrative Order on Consent ("AOC") Statement of Work ("SOW) and Comments on Interim Environmental Reports. Letter to Captain Marc Delao, Regional Engineer, Navy Region Hawaii from Mr. Omer Shalev, EPA Project Coordinator and Ms. Roxanne Kwan, DOH Interim Project Coordinator. October 29.

A second key assumption made by the Navy regarding the analysis of their thermal profile in the CSM is that the elevated temperature profiles in monitoring wells RHMW02 and RHMW03 were

caused by the LNAPL release from Tank 5. With regard to monitoring well RHMW03, the data indicates that the vertical zones of elevated temperature have existed since the vapor sampling ports were installed. The groundwater temperature in monitoring well RHMW03 measured during sampling has also remained unchanged at about 26.5°C since first sampled in 2005 to the present, indicating that the temperature profile recently measured by the Navy likely existed when RHMW03 was first drilled (EPA and DOH, 2018). During the drilling and the installation of the vapor sample points in 2005, the Navy reports that no evidence of petroleum contamination in the rock cores was detected by checking for odor and by screening with a photoionization detector (PID) (DON, 2007).

At monitoring well RHMW02, there are three reasons to question the Navy assertion that the elevated temperature profile is evidence of LNAPL.

- The first reason is that the temperature elevation is so slight that its occurrence (see Figure 7) is dependent on the choice of the background well. The background well used by the Navy is RHMW05, which is away from the influence of the main access tunnel. Among the possible factors affecting the temperature profile at RHMW02 besides biodegradation is the conduction into the vadose zone of the heat brought into the subsurface access tunnels by ventilation, which may lead to an overestimate of heat produced by any on-going biodegradation. The important influence of the main access tunnel on temperature is acknowledged by the Navy but it has not been quantified.
- The second reason is that if there is LNAPL that is undergoing biodegradation that causes a rise in temperature, that LNAPL may be from a fuel leak of unknown volume from Tank 6 reported by the Navy to the DOH in 2002 or other unreported fuel leaks from the RHBFSF.
- The third reason is that in-situ vapor probe responses around Tank 5 in the timeframe following the 2014 release can be interpreted as indicating that the primary vapor migration may have been to the northwest side of that tank and not in the direction of RHMW02 (see Figure 11). Actual LNAPL transport outcomes beneath Tank 5 in 2014 below the vapor probes is unknown; the conservative assumption based on this limited data is that transport was potentially to the northwest and is not represented with any certainty by the spatially limited monitoring well array.

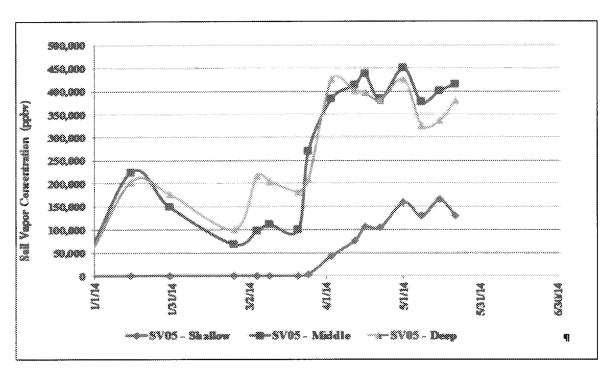


Figure 11 Soil vapor probe readings beneath Tank 5 following the January 2014 release. The deep probe is toward the outside of the tank corridor and the shallow probe closest to the tunnel. These data can be interpreted as initial release migration to the northwest of this Tank; note the shallow probe has low level detections that are not visible on a linear plot

Source: U.S. EPA and Hawaii Department of Health (EPA and DOH). 2018. "Approval to revise schedule for deliverables 6.3 - Investigation and Remediation of Releases Report and 7.1.3. - Groundwater Flow Model Report of the Red Hill Administrative Order on Consent ("AOC") Statement of Work ("SOW) and Comments on Interim Environmental Reports. Letter to Captain Marc Delao, Regional Engineer, Navy Region Hawaii from Mr. Omer Shalev, EPA Project Coordinator and Ms. Roxanne Kwan, DOH Interim Project Coordinator. October 29.

As part of the Groundwater Modeling Working Group Meeting held on August 1, 2019, the USGS expressed additional concerns with the Navy's unsupported assumptions and finding's regarding the thermal investigation presented in the CSM (USGS, 2019). Among the important conclusions in the USGS presentation is that there are no known published articles that have demonstrated that heat (temperature profiles) can be used to locate LNAPL bodies. Another important issue raised by the USGS during its presentation is that the Navy's CSM analysis of the thermal data should be checked in order to confirm that it properly accounts for effects of the tunnel and other infrastructure on the thermal profiles near the fuel tanks. In its presentation, the USGS demonstrated that the temperature drops faster in the areas of the tunnels because the surface temperature is maintained at only 80 feet above the water table.

The BWS continues to have serious concerns regarding the Navy's analysis of the thermal data and recommends that the entire section of the revised CSM report related to the Navy's thermal analysis be omitted as not technically defensible. Because the fate of fuel from the Tank 5 spill is of paramount importance to the conceptual model for LNAPL migration, the BWS

recommends that the Regulatory Agencies require the CSM be considered incomplete until the Navy has fully addressed both BWS and Regulatory Agency concerns regarding the validity of its thermal analysis.

#### **Summary of Comments**

The Navy's revised CSM does not provide an adequate basis for developing a groundwater flow model and the inherent deficiencies are such that it cannot be used to support an evaluation of contaminant transport pathways and the potential for receptor exposure. Specifically, the revised CSM fails to adequately address the considerable uncertainty associated with the Navy's characterization of the groundwater flow system and of the nature and extent of groundwater contamination at the RHBFSF. Moreover, the Navy analysis is incomplete, incorrect, and/or inconsistent with available evidence as it pertains to characterizing hydraulic gradients and certain important aquifer properties, like preferential flow pathways and saprolite. Many of these and other concerns have been repeatedly brought to the Navy's attention, but to date the Navy has either failed to address or has not adequately addressed them. Given the enormous amount of fuel stored, the location of the RHBFSF relative to our groundwater aquifer, and the potential for impacts to Oahu's critical drinking water resources, the BWS requests that the Regulatory Agencies reject the Navy's revised CSM report and require that the Navy upgrade the RHBFSF tanks with secondary containment or relocate them away from our sole-source groundwater aquifer.

Thank you for the opportunity to comment. If you have any questions, please contact Mr. Erwin Kawata, Program Administrator of the Water Quality Division, at 808-748-5080.

Very truly yours,

Manager and Chief Engineer

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